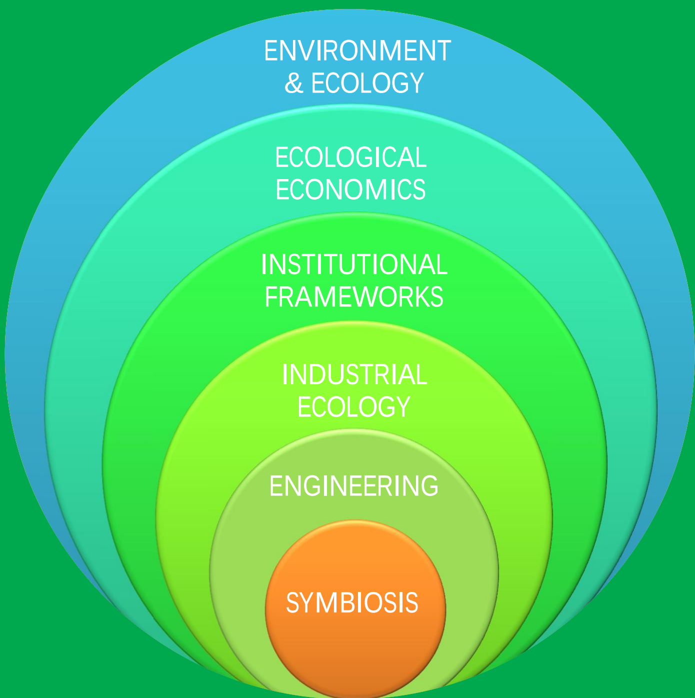
Department of Forest Products Technology

Opportunities and Barriers in the Beneficial Utilisation of Process Industry Residues

...from resource efficiency towards sustainability philosophy

Gary Watkins



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Opportunities and Barriers in the Beneficial Utilisation of Process Industry Residues

...from resource efficiency towards sustainability philosophy

Gary Watkins

A doctoral dissertation completed for the degree of Doctor of Science in Technology to be defended, with the permission of the Aalto University School of Chemical Technology, at a public examination held in Auditorium L1 (Forest Products Technology Department, Building 1) at Aalto University, School of Chemical Technology (Espoo, Finland) on the 13th June 2014 at 12 noon.

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Abstract

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Abstract

This doctoral dissertation describes novel material efficiency possibilities that exist within the forest products and ferrous metals sectors, the associated opportunities for, and institutional barriers to, solid residue utilisation within the Bothnian Arc Region in Western Finland. The way in which industrial symbiosis and industrial ecology approaches can be applied to the cooperation of multiple formerly separate industrial sectors is investigated, including the inter-industry utilisation of production residues for the manufacture of novel residue-based symbiosis products. A multidisciplinary research methodology is used to analyse: potential inter-industry cooperation to achieve improved eco-efficiency to support sustainable development, the residues involved, their characteristics, current and potential utilisations, novel inter-industry symbiosis product ideas and their environmental performance. The important issue of how symbiosis can be encouraged through addressing institutional aspects for residue handling and the changes that would support increased opportunities for efficiencies are explored and timely yet practical recommendations made to support this. Recommendations include requiring new approaches based on the waste hierarchy and life-cycle thinking, as well as further clarification of the implications of 'end-of-waste' legislation and criteria for product systems with multiple residue streams. Other recommendations encompass the application of best available techniques approaches to material efficiency and waste recovery in process industry environmental regulation and guidance, as well as addressing implications of the chemical safety of residue streams and residue-based products. Findings suggest that EU instruments claiming to encourage a comprehensive approach to sustainability, including consistency between various instruments, also need to be bolstered by integrated industry related instruments and soft law type approaches acting as guidance at appropriate levels. An overaching theoretical effort in this dissertation asks whether efficiency seeking is capable of delivering sustainable systems under the dominant paradigm of ecological modernisation if the absolute decoupling of industrial production from environmental impacts depends on wider systemic aspects. The incommensurability of the paradigmatic basis of industrial symbiosis with that of a wider, more sustainable form of industrial ecology is also explored and a case made for the continued application of both through support for pluralism in our ecological metaphors.

Keywords eco-efficiency, sustainability, industrial symbiosis, industrial ecology, solid residue, waste policy, recycling, end-of-waste, institutional barriers, symbiosis products, life cycle assessment

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Tiivistelmä

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Tiivistelmä

Tässä väitöskirjassa kuvataan mahdollisuuksia tehostaa metsä- ja metalliteollisuuden materiaalitehokkuutta, tavoitteena lisätä teollisuuden kiinteiden sivuainevirtojen hyödyntämistä, sekä selvitetään mitä hallinnollisia esteitä kehitystyössä on. Tutkimuksessa selvitetään miten teollisen ekologian ja teollisten symbioosien lähestymistapaa voidaan soveltaa useiden erillisten teollisuudenalojen yhteistyön tukemisessa siten, että eri teollisuudenalojen sivuainevirtojen hyödyntämistä voitaisiin lisätä, esimerkiksi uusien symbioosituotteiden valmistuksessa. Tutkimuksessa on käytetty monitieteistä tutkimusmenetelmää seuraavien seikkojen analysointiin: mahdollinen toimialojen välinen yhteistyö ekotehokkuuden lisäämiseksi ja kestävän kehityksen edistämiseksi, syntyvien sivuainevirtojen ja niiden ominaisuuksien selvittäminen, nykytilan ja uusien hyödyntämismahdollisuuksien kartoittaminen, sekä uusien teollisten toimialojen välinen symbioosituoteideoiden ja niiden ympäristösuorituskyvyn selvittäminen. Tutkimuksessa käsitellään erityisesti sivuainevirtojen hyödyntämiseen liittyviä hallinnollisia näkökohtia sekä niitä tekijöitä, jotka tukevat materiaalitehokkuuden edistämistä. Väitöskirjassa esitetään myös materiaalitehokkuutta lisääviä ajankohtaisia ja käytännöllisiä suosituksia, mm. jätehierarkia ja elinkaariajattelu sekä end-of-waste -lainsäädännön ja -kriteerien vaikutukset teollisille systeemeille, joilla on useita erilaisia sivuainevirtoja. Edellä mainittujen lisäksi työssä esitellään miten parhaiden käytettävissä olevan tekniikoiden (BAT) lähestymistapaa voidaan soveltaa materiaalitehokkuuden lisäämisessä ja jätteiden tehokkaammassa hyödyntämisessä, sekä miten ympäristölainsäädännön ja –ohjauksen kautta voidaan joko edistää tai hidastaa sivuainevirtojen hyödyntämistä prosessiteollisuudessa ja mikä vaikutus sivutuotteista valmistettujen tuotteiden kemikaaliturvallisuutta koskevien asioiden käsittelyllä on kokonaisuuteen. EU:ssa on kehitetty ohjauskeinoja, joiden toivotaan tukevan kestävää kehitystä. Tärkeää kestävän kehityksen edistämisen kannalta on, että nämä keinot, kuten lainsäädäntö ja soft-law tyyppinen lähestyminen, toimivat yhdessä johdonmukaisesti ja että ne olisivat tarkoituksenmukaisia. Tutkimuksen hallitsevana teoreettisena teemana on kysymys siitä, voiko pyrkimys tehokkuuteen tuottaa kestäviä systeemejä hallitsevan ekologisen modernisaation paradigman alla, jos teollisen tuotannon ja ympäristövaikutusten irtikytkentä on riippuvainen laajemmista systeemisistä seikoista. Argumentoinnin kohteena on myös teollisen symbioosin paradigmaattisen perustan yhteismitattomuus laajemman, kestävämmän teollisen ekologian muodon kanssa, mukaanlukien molempien lähestymistapojen soveltaminen tukemalla pluralismia metaforioiden käytössä.

Avainsanat ekotehokkuus, kestävä kehitys, teollinen symbioosi, teollinen ekologia, kiinteät teolliset sivuainevirrat, jätepolitiikka, kierrätys, end-of-waste, institutionaaliset esteet, symbioosituotteet, elinkaariarviointi

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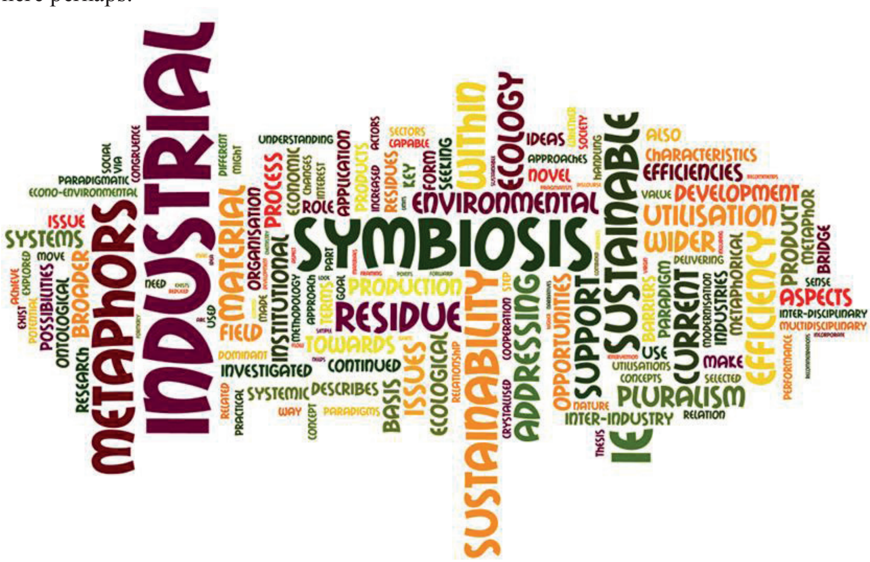
‘The world we have made, as
a result of thinking we have done thus far, creates
problems we cannot solve at the same level of thinking at which we created them.’
Albert Einstein, 1946

‘Today’s problems come from yesterday’s solutions.’
Peter Senge, 1990

Preface

The research work and thesis presented in this dissertation was carried out at the Department of Forest Products Technology at Aalto University in Espoo, Finland during the period 2007-2013. Part of this research was conducted under the research project Pro-environmental Product Planning in a Dynamic Operational Environment Now and in Future - Methods and Tools (ProDOE) which was part of the Finnish Academy Research Programme on Sustainable Production and Products (KETJU), support from which is greatly appreciated. This thesis was developed as part of the multidisciplinary ProDOE Research Group's work and draws on the synergy and excellent work relationships formed therein.

A justification for the number of publications that form the corpus of this dissertation and a word of explanation concerning the breadth and depth of these studies, as well as my reasons for pursuing such a range of research and the difficulties involved, is needed here perhaps.



As a member of ProDOE I was exposed to a stimulating array of other researchers' ideas and topics; although ostensibly focussed on the project objectives related to the characteristics of specific process industry residue materials, I soon found that I had a growing interest in the broader themes of our research group and wanted to contribute to research on multiple project sub-hypotheses. I was simultaneously designing and teaching courses on environmental management and industrial symbiosis whilst carrying out this research and this led me inevitably to question the specific focus of materials efficiency studies within the broader concept of sustainability. This broader focus has led me to adopt a more multidisciplinary research approach that required a suitable methodology which could utilise a wide range of research material, particularly that arising from the emerging interdisciplinary field of industrial ecology.

There is also a sense of evolution in the themes of my published articles, one that has extenuated the initial focus on specific material studies and expanded the breadth of the synthesis over the research period involved. The challenge was to uncover the implications for interesting materials case studies and this was achieved by researching not only their material characteristics and utilisation potential, but also the institutional drivers and barriers to their environmentally beneficial utilisation. The use of both industrial symbiosis and industrial ecology metaphors by the ProDOE research group also needed to be addressed in my own mind due to their apparent differences in focus. This thinking and approach has resulted in the compilation dissertation at hand which draws together the contributions from published articles and describes ways in which institutional aspects can be addressed to achieve policy goals, but it also explores and discusses fundamental issues with the theoretical dimensions of ecological metaphors and implications arising from their execution in more depth.

Firstly, I would like to thank my supervisor Professor Olli Dahl[1] for giving me his invaluable guidance, solid support and the freedom to explore different avenues of interest. I would also like to thank Hannu Nurmesniemi[2], Risto Pöykiö[3] and Jyrki Heino[4] for all their help and advice, Roope Husgafvel[1], Inga-Liisa Paavola[5], Lauri Linkosalmi[1], Mari-Linda Harju-Oksanen[5] and Harri Nordlund[1] for excellent co-author teamwork, as well as all the other members of the ProDOE research team including Maaria Wierink[1], Sanni Eloneva[1], Eeva-Maija Puheloinen[5] and Professors Kari Heiskanen[1], Ari Ekroos[5] and Olli Salmi[6]. There are also numerous other people without whose help and assistance this dissertation would not have been possible including Ilkka Välimäki[7], Raimo Lilja[8] and Matias Warsta[1]. I would especially like to thank both Mikko Mäkelä[1] for his co-authorship, energy and friendship, and Nani Pajunen[1] for her excellent collaboration on some key papers as well as for the success of our mutual support pact! Thank you all so very much!

Last, but by no means least, I would like to thank my wife Mervi and daughter Mia for all their love and encouragement, as well as all my other family and friends for their support, patience and understanding throughout my extended period of study.

Helsinki, 28th April 2014

Gary Watkins

[1] Aalto University
[2] Stora Enso Oyj
[3] City of Kemi
[4] University of Oulu
[5] University of Helsinki
[6] VTT (Technical Research Centre of Finland)
[7] Suomen Ympäristöpalvelu Oy
[8] Ekoleima Ay

List of Publications

This dissertation consists of an overview of the following seven publications, which henceforth are referred to in Roman numerals in the text:

I **Watkins, G.,** Mäkelä, M., Dahl, O. (2010) Innovative use potential of industrial residues from the steel, paper and pulp industries - a preliminary study. *Progress in Industrial Ecology - An International Journal 7(3)*, 185-204.

II Pajunen, N., **Watkins, G.**, Wierink, M., Heiskanen, K. (2012) Drivers and barriers of effective industrial material use. *Minerals Engineering **29***, 39-46.

III **Watkins, G.**, Husgafvel, R., Pajunen, N., Dahl, O., Heiskanen, K. (2013) Overcoming institutional barriers in the development of novel process industry residue-based symbiosis products - Case study at the EU Level. *Minerals Engineering **41***, 31-40.

IV Pajunen, N., **Watkins, G.**, Husgafvel, R., Dahl, O., Heiskanen, K. (2013) The challenge to overcome institutional barriers in the development of industrial residue-based novel symbiosis products - Experiences from Finnish process industry. *Minerals Engineering **46-47***, 144-156.

V Mäkelä, M., Harju-Oksanen, M-L., **Watkins, G**., Ekroos, A., Dahl, O. (2012) Feasibility assessment of inter-industrial solid residue utilization for soil amendment - Trace element availability and legislative issues. *Resources, Conservation & Recycling **67***, 1-8.

VI Husgafvel, R., Nordlund, H., Heino, J., Mäkelä, M., **Watkins, G**., Dahl, O., Harju-Oksanen, M-L., Paavola, I-L. (2013) Utilization of multi-stream residues from integrated pulp and paper, and carbon steel mills as raw materials for potential secondary products - What is their legal status and could there be environmental benefits? Submitted to *Journal of Industrial Ecology.*

VII Husgafvel, R., **Watkins, G.**, Linkosalmi, L., Dahl, O. (2013) Review of sustainability management initiatives within Finnish forest products industry companies - Translating EU level steering into proactive initiatives. *Resources, Conservation and Recycling **76***, 1-11.

Author's contribution

I Gary Watkins carried out the literature review in collaboration with Mikko Mäkelä and wrote half of the manuscript.

II Gary Watkins carried out the literature review in collaboration with Nani Pajunen and wrote half of the manuscript.

III Gary Watkins carried out the literature review, devised the conceptual approach, interpreted the results in collaboration with Roope Husgafvel and Nani Pajunen; and wrote half of the manuscript.

IV Gary Watkins carried out the literature review and devised the conceptual approach in collaboration with Nani Pajunen and Roope Husgafvel; and wrote half of the manuscript. Nani Pajunen conducted the empirical study of industry.

V Gary Watkins was responsible for responsible for devising the original conceptual approach to designing symbiosis products writing part of the manuscript in collaboration with Mikko Mäkelä and Mari-Linda Harju-Oksanen.

VI Gary Watkins was responsible for devising the conceptual approach and writing part of the manuscript concerning industrial symbiosis, legal aspects and products issues in collaboration with Roope Husgafvel who carried out the life cycle assessment analysis; and Harri Nordlund who carried out the exergy analysis.

VII Gary Watkins carried out the literature review and interpretation of results in collaboration with Roope Husgafvel; and wrote half of the manuscript. Lauri Linkosalmi carried out the empirical study of companies.

Nomenclature:

Abbreviations:

BAT	best available techniques
BAU	business-as-usual (*idiomatic*)
BPA	by-product assessment
CP	cleaner production
EC	European Commission
ECJ	European Court of Justice
EE	ecological efficiency or eco-efficiency
EoW	end-of-waste
EU	European Union
GBFS	granulated blast furnace slag
GWP	global warming potential
IED	Industrial Emissions Directive (EU)
IS	industrial symbiosis
IE	industrial ecology
IIP	Integrated Industrial Policy (EU)
IPP	Integrated Product Policy (EU)
IPPC	integrated pollution prevention and control
LCA	life cycle assessment
MEf	material efficiency
MOTIVA	Finnish State owned company for promoting efficient and sustainable use of energy and materials (Motiva Oy)
NISP	National Industrial Symbiosis Programme (UK)
NPE	non-process element
REACH	Registration Evaluation Authorisation and Restriction of Chemicals (EU)
SD	sustainable development
WFD	Waste Framework Directive (EU)
WPr	waste prevention
WRAP	Waste & Resources Action Programme (UK)

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1 Introduction

The great challenge to our economy today is to determine whether integration in the paths of environmental sustainability and economic growth can be achieved, and if so, how. By simply doing more with less, or perhaps in many cases simply achieving the same with much less, would seem to offer to help balance the environmental impacts of growth with the carrying capacity of the environment. To illustrate one option, so called *ecological thinking* can be an opportunity for all actors in this respect, where saving virgin raw-materials, maximising the utilisation of by-products and residues, thereby reducing the environmental impacts of resource extraction and waste, might be the *win-win-win* situation for our industry, us as stakeholders and for our environment.

The utilisation of process industry residues, by-products and waste materials is still at a fairly early stage of development and needs to be actively studied and supported further. In order to reduce the amount of material falling to be managed as waste via final disposal to landfill it is essential that innovative ways are found to beneficially utilise production residues. The material characteristics of candidate residues is only the first part of the problem, the identification of any material recycling possibilities must then be supported by institutional aspects that include the thinking and cooperation of actors, the policies and legislation needed to enable such utilisations and help overcome barriers. It is this multi-faceted approach and the notion that ecological metaphors for industrial organisation can help that is the subject of this research.

Our society, its industries and ourselves as individuals are starting to realise that we live in a closed environment system with scarce resources. Resource system dynamics and their interaction with our society is a major ingredient of the growth in our consciousness as actors. However, in order to more fully understand resource systems we need to better grasp the very complex interplay between system dynamics, human behaviour and material cycling. The physical constraints to our actions due to the laws of thermodynamics, as well as the effects of the design of products and the materials used in them, the performance of products and their lifecycle, system architecture and economics, as well as the effects of institutional aspects such as policy making and law, all have an influence. In this respect, the means by which society's industry and economy might more effectively assist industrial processes to move towards more environmentally sustainable operation and development models is receiving intense research attention. Issues that immediately come to the fore in such research is the need to clarify the idea of *industrial symbiosis* (IS) within the field of *industrial ecology* (IE) and to explore the implications of their operationalisation for science and engineering operating within the wider institutional context of society and its economy.

The main focus of this work is on the advantages available to the steel, pulp and paper sectors through the application of IS ideas to their process residues via recycling into the manufacture of novel, lower environmental impact products. The characteristics of selected residues are also reported in order to illuminate opportunities for symbiosis products and their beneficial utilisation other than reliance on landfilling as a management option. Although the main emphasis is on the local technological scope for specific inter-industry symbioses between embedded industrial sub-processes (where some of the main processes themselves could be viewed as inherently unsustainable), an attempt has also been made to acknowledge and explore the more complex non-technical dimensions involved with IS and the wider fabric or broader concept of IE within which it needs to operate (Baas and Huisingh 2008).

New European Union (EU) policy and law now means that waste management requires new approaches based on applying a waste hierarchy of preferred management methods in the order: 1) waste prevention, 2) preparing for re-use, 3) recycling, 4) other recovery (such as energy recovery), down to the least preferred option of 5) disposal. Life-cycle thinking is now also called for in product design, as is work on the opportunity to seek clarification on when production residues can achieve so called *end-of-waste* (EoW) status in law and be more easily used as secondary raw materials to help increase resource efficiency and reduce waste disposal problems and their environmental impacts.

New ways to encourage and promote these types of work are vital. Arrangements for improving co-operation between actors are key issues to encourage innovation in new ways to reuse residues and generate useful by-products in the production and supply chain. To achieve notable progress the need for change cannot be overstated. The closure (including optimisation) of resource cycles can only be achieved if all the chemical, physical, technical, economic, legal, administrative, environmental and social issues are considered together in a systemic way. The broader goals of our economic system and ways in which to guide improvements towards more sustainable approaches requires the identification and development of workable incentives and drivers, as well as the dismantling of barriers.

Systemic approaches are crucial for this to progress towards environmentally preferable solutions and responses. Taking a more holistic[9] approach to the subject of beneficial utilisation of process industry residues requires a non-standard research methodology, which in turn demands a more expansive and eclectic approach to the focus of research publications. In this respect this is a new approach to addressing these issues and helps advance the solving of environmental sustainability problems through multidisciplinary approaches.

1.1 The Challenge

Sustainable development (SD) has now been established as the leading global development paradigm[10] that also covers sustainable industrial development. The process of moving towards the sustainability goals outlined in the Brundtland Report (WCED 1987) and restated in multiple United Nations (UN) and EU instruments will require innovative approaches to resource use in accordance with overall sustainable development of industry and the sustainable use of natural resources (EC 2005a; EC 2011c; UN 2002; UN 2013). It is becoming clear that addressing the issue of sustainability requires a focus on specific limited resources, their throughput and total mass flow within the system and across various locations. However, systems that are capable of supporting human development in the long-run must recognise the limits of a finite planet and its resources (Daly 1996; UK Sustainable Development Commission 2009) and such a sustainable world will require increased focus on integrated *industry-society-environment* interactions to ensure responsible approaches to industrial activities (Graedel and Allenby 2010). In this respect the economic recycling of materials is an extremely timely and important topic to be addressed, with the attempted closure of material cycles as the ultimate goal (Reuter et al. 2005).

Put simply, it can be claimed that the most efficient way to decrease the environmental load discharged to air and water from a particular process industry is to increase the

[9] *Holistic* - approach where the entire system is considered and an attempt is made to reveal properties on the system level.
[10] *Paradigm* - implicit or explicit view of reality.

process yield/product (or the amount of solid wastes) (Dahl et al. 2008). This simple relationship means that on a quantitative basis, those process raw materials and additives that do not end up in the final product are the main materials that contribute to the environmental load arising from a particular process. If the resulting process residues arising from reduced environmental load to air and water could then be utilised further, to increase the yield of total products, then the overall eco-efficiency[11] of an installation will be increased (**Figure 1**). In this respect the utilisation of process wastes and by-products is an economically and environmentally eligible objective and has direct benefits of resource and energy conservation (Castro et al. 2009).

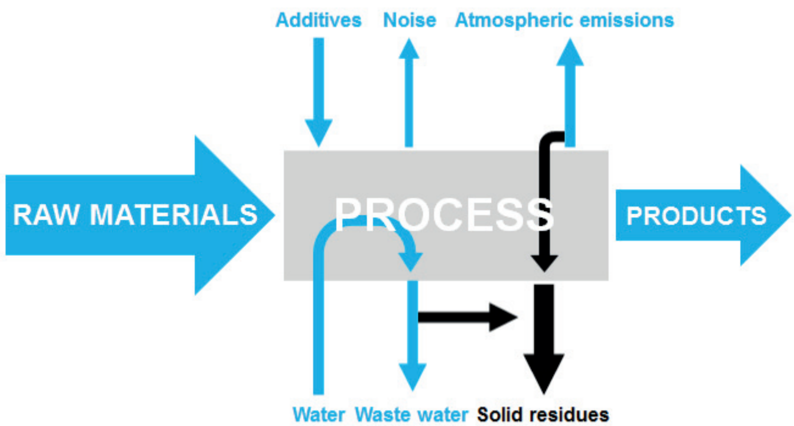

Figure 1 *Environmental burdens generated by a unit process (modified from Dahl et al. 2008)*

The main principles of EU policy on industry and sustainable use of natural resources and recycling of solid wastes are considered to be important factors within process industry in minimising the generation of solid wastes and contributing to material efficiency industry (Sorvari 2008).

The application of an ecological metaphor by way of industrial symbioses between pulp and paper, and the ferrous metals sectors' residue streams holds the potential of achieving a spectrum of various concepts worthy of research consideration. Here, if markets and uses exist for potential symbiosis products and if proper standards could be developed, and if they could be proven to be environmentally sound, it would be worthwhile to assess whether potential residue-based symbiosis products such as land ameliorants and conditioning agents and cement replacement applications, for example, could achieve *end-of-waste* (EoW) status (EC 2008c) in order to be considered as actual products.

Understanding the dynamics of IS requires focus on the factors that stimulate or hinder the process (Boons et al. 2011). In view of this, the critical assessment of the current management approach for residues (the treatment of residues as waste in particular) and development of institutional arrangements to support drivers for advancing environmentally beneficial approaches and the dismantling of barriers to utilisation is justifiable. The use of an IS approach to the transformation of industrial systems and sub-systems, from linear towards more closed loop models in analogy to the cyclical flows of ecosystems, involves the participative overlapping and integration of different processes and systems to achieve symbiotic efficiencies wherever possible.

[11] *Eco-efficiency* - ecological efficiency.

There has also been a slowdown in improvement of the environmental performance of process industries over recent years with *best available techniques* (BAT), concerning emissions control, having already been successfully integrated into operations during the 1990s (Silvo et al. 2009). Large step-change decreases in emissions have not occurred in the industry since. New types of action from the public and private sectors are therefore needed if development of further environmental innovations are to be progressed. Improved environmental performance needs to be supported by technological innovations, environmental policies and due consideration of market requirements (Kivimaa 2007).

The challenge is to identify new ways forward.

Trans-disciplinary science

Many of the concerns and methods of industrial ecology (IE) overlap with those of researchers in other fields and as a highly inter-disciplinary emerging field IE has its own epistemological[12] and ontological[13] issues. In some ways IE has been described as a field of study with multiple ontologies that attracts scientists, technologists, and social scientists to the subject matter, and to some extent is reflexively generating its own social critique (Allenby 2006). The breadth of fields involved under the umbrella of IE and their general themes can be extensive, ranging from engineering and science, ecology and ecological economics, through to the softer social sciences, indeed 'mutually exclusive ontologies' as a barrier to integration of the field have been claimed by one author (Allenby 2006).

Contributions to the field of IE may therefore spring from many sources (**Figure 2**) and this raises ontological issues. What is the role for IE practitioners in the future? In view of the epistemological issues, there are also issues with the various metaphors and models utilised in industrial ecology (IE) and industrial symbiosis (IS), their meaning and operation in view of the prevailing economic and scientific paradigms within which they try to operate. Similarly, a discussion of the barriers to trans-disciplinary work and philosophical issues concerning the science involved that may also hamper progress is worthy of discussion. The role of broader, recently prevalent global cultural drivers in the form of socio-economic aspects and ideologies, and whether traditional approaches to industrial production are now being questioned because of the level of perceived threats to our global environment, also need to be discussed. Essentially, the broader questions are whether current systems of industrial production can utilise IS ideas and thereby progress towards broader IE ideas and ultimately towards sustainable development, and whether they are currently caught between the industrial ecology metaphor (an *ecology* focus) and the industrial symbiosis metaphor (an *industry* focus).

The dominant paradigm in education, science and research is still a reductionist[14] one hence scientists are often deeply embedded in a reductionist approach in a narrow field

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[12] *Epistemology* - nature of the relationship between the knower (inquirer) and the known or knowable. How can human beings obtain knowledge of truths about the world? How can they assess the reliability of that knowledge?

[13] *Ontology* - a set of particular assumptions about the nature of being and reality. What objects exist in the world? What statements about these objects are true?

[14] *Reductionism* - (a) an approach to understanding the nature of complex things by reducing them to the interactions of their parts, or to simpler or more fundamental things or (b) a philosophical position that a complex system is nothing but the sum of its parts, and that an account of it can be reduced to accounts of individual constituents.

and the broader environmental context and the implications of reductive science are not fully appreciated. A provocative question that this thesis discusses therefore, one that speaks to a much wider controversy, is the contention that there needs to be a level of necessary metaphorical pluralism in the use of ecology and symbiosis metaphors as vocabulary that assists discourse on more sustainable approaches. Can these metaphors offer a way forward without a fabric of wider frames for society's institutions supporting such an approach? Do they make any sense as a useful part of the current economic paradigm? How might pragmatists try to incorporate ecological metaphor ideas into current practices? Could they make more sense as part of a different narrative? What are the immediate problems and possible solutions so we can move forwards? What is the predicament we face when thinking about sustainability as a realistically achievable process and how can we respond to this challenge?

Ecology – Metaphor, systems model, diversity, web of interdependence of organisms and their environment, complex adaptive systems, life cycles, material and energy cycles.

Ecological Economics – Environmental and economic sustainability, cost benefit, coupling and complexity of systems, market paradigms, stocks and flows, growth and degrowth, ecological limits, industrial production, eco-efficiency.

Social sciences – Language of social reality, structures, institutionalisation, actors and networks/fabrics, ontological discourse, epistemological interaction, ideology, language, metaphor and paradigms, social construction of technology.

Science and Engineering – Chemistry, physics, thermodynamics, systems, applied sciences, pollution control, models, material cycles, industrial processes technology, cleaner production, material flow balance, resource efficiency, life cycle assessment.

Figure 2 *Contributions to the field of industrial ecology - multidisciplinary practitioners*

1.2 Scope, objectives and hypothesis

This dissertation aims to research and propose means by which society's industry and the economy within which it operates might be better able to approach opportunities for, and begin to address overcoming barriers to, the utilisation of process industry production residues to more effectively assist selected industrial processes to move towards more environmentally sustainable operation and development models. The manufacturing of novel symbiosis products based on the recovery and recycling of inter-industry residue flows is a very important, timely and logical objective since major instruments such as the EU's Waste Framework Directive (2008/98/EC) (WFD) (EC 2008c) and supporting policy aims at achieving more sustainable resource use and improved overall resource efficiency in society.

The theoretical framework behind this approach is *industrial ecology* (IE) which involves systemic thinking on industrial systems as networks of multiple processes and flows. In addition, *industrial symbiosis* (IS) as a part of this broader IE framework focuses on, for instance, the utilisation and interaction of those processes and flows within the overall industrial ecosystem. Development of novel symbiosis products based on process industry residues could be one utilisation option that allows the bringing together of inter-industry flows (contributing to more closed material cycles across wider systems) and also the formation of new processes in a network. In short, Graedel and Allenby (2010) stress that a sustainable world will require increased focus on integrated *industry-society-environment* interactions to ensure responsible approaches to industrial activities, noting that IE aims at creating adaptable and responsive approaches to sustainable development. Waste recovery through recycling reduces the amount of industrial waste produced and in the case of symbiosis products it contributes many further benefits, being not only in accordance with the objectives of the WFD, but going beyond waste reduction towards more sustainable and efficient use of resources and materials.

The common use of *waste* and *residue* as interchangeable terms does not generally aid in clarifying issues during the discussion of beneficial utilisation of materials and so the term *residue* is used unless the status of a material as 'waste' appears to be clear from a legal point of view and/or it is consigned to another holder as a waste as common practice. The issue of terminology is very important here since we are concerned mainly with research into material utilisation and not waste treatment.

This dissertation includes selected studies on the recycling potential of residue materials from heavy process industries such as integrated pulp and paper mills, carbon steel plants and mining operations, for use in land amelioration, as construction materials and utilisation as secondary raw materials for use in novel symbiosis products (**Figure 3**). Residue-based products such as soil amelioration pellets, low competence concrete and mine filler concepts, and the demonstration of the potential for this kind of waste utilisation approach to be a more sustainable option for industrial residue management, is a prime focus. The contribution that Finnish process industries can make in terms of improved material efficiency and a reduction of environmental impacts from production, particularly in the case of the ferrous metals and the pulp and paper sectors, are used as examples for illustrating residue recycling and symbiosis opportunities for residue-based product development.

Questions that immediately arise are: What are the current management arrangements for the target industries' high volume residues such as solid slags, ashes, grits and dregs? What are the barriers to utilisation arising from the material characteristics of these residues? What are their possible utilisations? What are their environmental performances? What are the policy and legal barriers to utilisation? How can institutional barriers be dismantled and incentives introduced? Are there organisational barriers? Do ecological metaphors assist in seeking solutions to specific problems and broader responses to the dilemma posed to our industry by sustainable development?

The main policy and legal research objective is to outline new ways to extend policy instruments, regulate and control the use of industrial by-products and residues. Where increasing the use of secondary materials and by-products can be shown to be more environmentally sustainable, new policies that not only encourage this through helping overcome economic barriers but also dictate goals and promote the research and innovations required to make greater use of such materials are needed.

A further aim of this work is to support informed decision-making by both process industry and public authorities since, according to Ashton (2009) interactions among actors and external forces can cause permanent changes within regional industrial ecosystems, and policy choices and cooperation among actors can be used to organise resources in a way that maintains the functionality of the overall system.

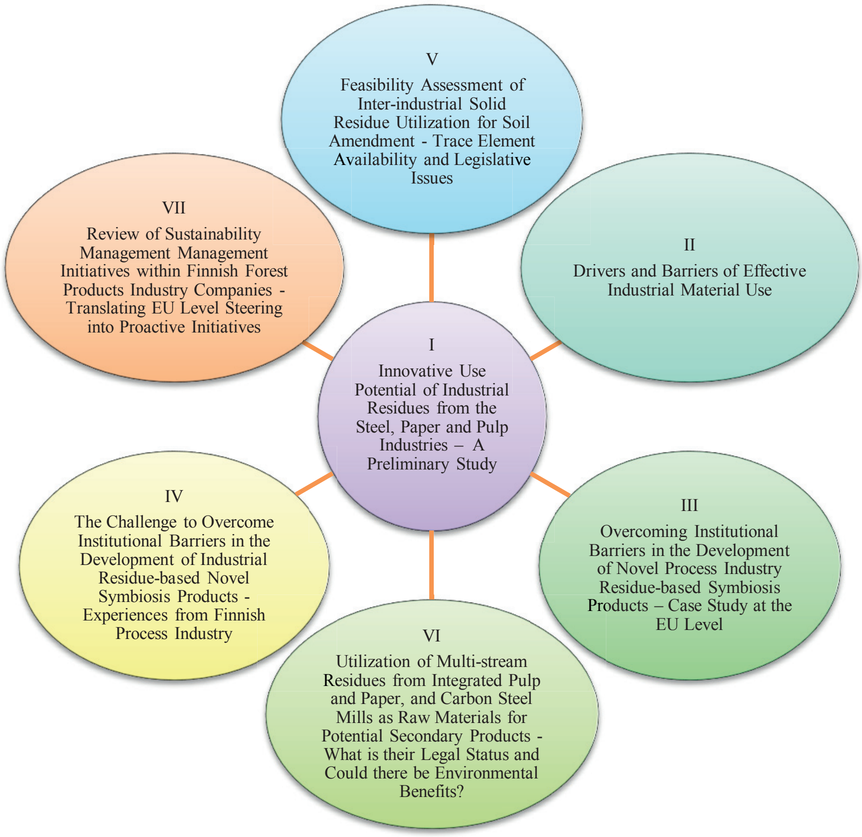

Figure 3 *The publications in this dissertation*

A final theme was to research and attempt to clarify the position of IS within the field of IE and to explore the implications for the operation of these metaphors in engineering and the wider institutional context of society and the economy. Are there issues concerning the meaning and operation of these ideas and metaphors in terms of the prevailing economic and scientific paradigms? Are there also trans-disciplinary barriers and issues concerning the science involved? Is there a role for IS in paving the way for broader IE thinking which according to Ehrenfeld (2008) can then act as a bridge in changing key cultural beliefs and norms?

My broad research hypotheses are:

- The closure (including optimisation) of resource cycles can only be achieved if all the chemical, physical, technical, economic, legal, administrative, environmental, and social issues are considered together in a systemic way.
- That policy must be discussed from the perspective of all actors.
- We need to understand the implications of the metrics and procedures used as well as the normative aspects of paradigmatic changes in our approach to industrial production.

The publications that form this dissertation are illustrated in **Figures 3** and **4**. **Paper I** gave an overview of the steel, pulp and paper process industries that are the focus for further research and describes the types and general characteristics of the main residue streams that arise in the chosen process industries, the background to their utilisation world-wide and explored some residue-based symbiosis product concepts. **Papers II, III** and **IV** then looked at the current drivers for, and barriers to, residue utilisation in the EU and in Finland in terms of the institutional changes that may be needed to promote drivers and overcome barriers. **Papers II, III, IV** and **V** discussed the EU's legislative framework surrounding the issue of waste classifications, the definition of waste and *end-of-waste* (EoW) criteria, and whether legislation improved drivers or erected more barriers to residue utilisation. Symbiosis product concepts were further investigated in **Paper V** which addressed the characteristics of specific product concepts and the legislative issues surrounding their beneficial utilisation.

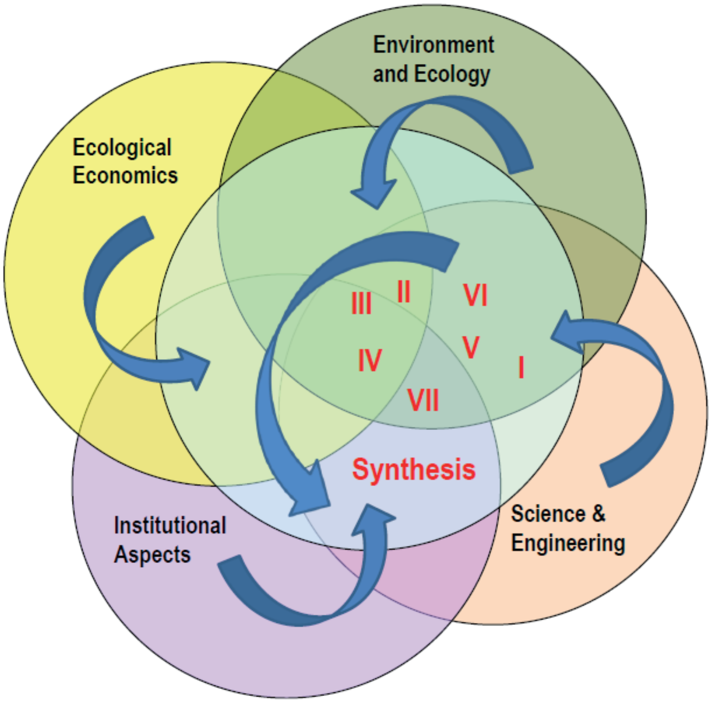

Figure 4 *Relationship of published articles to the broad research fields of interest*

Paper VI then investigated and discussed the demonstration of symbiosis product characteristics in terms of their improved environmental performance, sustainability, product development potential and legal aspects. **Paper VII** then identified key gaps in sustainability management and asked whether industrial symbiosis has a role in the forest sector's response to the sustainable development challenge in particular. Finally, the extended synthesis and discussion also explores in more depth the broad paradigmatic issues implicit in the application of the industrial symbiosis and industrial ecology metaphors and identifies the challenges faced in attempting to apply such ideas in society.

The specific research questions that flowed from the broad hypotheses were:

- **Paper I -** What is the background to steel, pulp and paper residue symbioses worldwide? Are symbiotic product ideas worthy of further research? What might be the characteristics of possible symbiosis product ideas?

- **Papers II, III, IV** and **V -** What are the drivers and barriers to residue utilisation and what role do they play? Are stronger institutional arrangements needed at both domestic and EU levels? What are the current practical uses of residues in industry? What will be the new, future drivers? How can barriers be addressed especially in relation to waste policy and law? What are the focus areas at the Finnish national level? What are the implications for development of residue-based symbiosis products? Does material efficiency have a role to play in environmental permitting? What practical solutions are possible and how can these be encouraged in Finland? Has recent legislation improved drivers or erected more barriers?

- **Paper V -** What is the performance of residue-based product concepts in terms of their potential as virgin product replacements, their relative sustainability and legal issues? Can benefits of symbiosis products be demonstrated? What does the law say concerning symbiosis products?

- **Papers VI** and **VII -** Can the environmental benefits (in terms of Global Warming Potential (GWP)) of symbiosis products be demonstrated using life cycle assessment (LCA) and exergy analysis? What is the scale of potential symbiosis product replacements? What are the key elements and gaps in sustainability management in Finnish process industry initiatives? What is the forest industry outlook on sustainability issues? How can the gap between industry initiatives and environmental steering at the EU level be bridged? What are the key elements in the forest sector's response to the challenge of sustainable development? Do IS and IE have a role to play?

2 Materials and methods

2.1 Research approach

This subject matter and approach raised issues concerning the choice of an appropriate research methodology. In order to realise the objectives of this thesis, a multidisciplinary scientific approach was taken where subjects in the fields of chemistry, engineering, ecology, economics, sociology and law were used and combined via a multidisciplinary research methodology, with both theory and empirical data having been utilised.

2.1.1 Research strategy and process

The subject matter for this research included both convergent and divergent problems as described by Schumacher (1973) (**Figure 5**), where convergent problems are those for which attempted solutions may gradually converge on one solution or answer; cf. Kuhn (1962) and the convergence of technological solutions. Divergent problems are those that do not tend to converge on a single solution; something that is a core characteristic of complex systems such as societies.

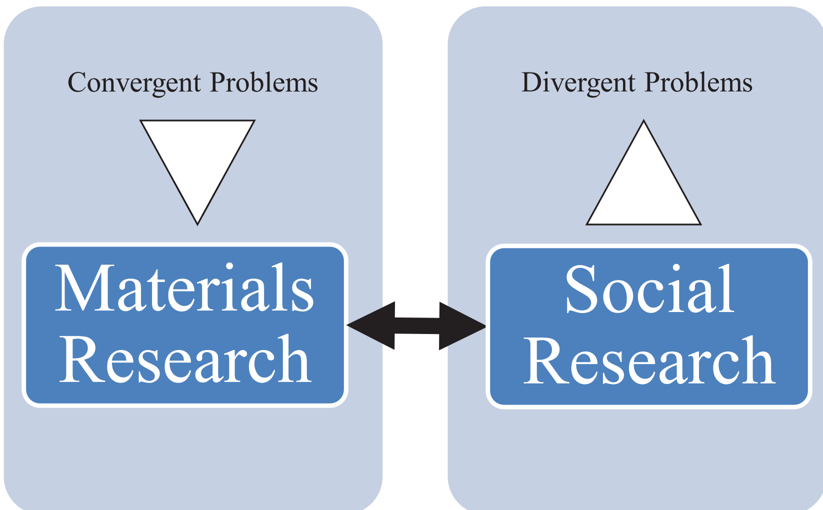

Figure 5 *The need for multidisciplinary research*

The approach taken to this compilation dissertation was therefore one where a strong theoretical element and the frames it creates are compared to images derived from empirical data as evidence.

In order to realise the overall research objectives a multidisciplinary approach was called for where both theory and empirical data are utilised. The problem definition is based on relevant theory and empirical data. The analytical framework is built on theory. Images are constructed from empirical data. The conclusions and recommendations are found in a retroduction[15] between theory, methodologies and empirical data (**Figure 6**) cf. Amundsen (1999). According to Ragin (1994) retroduction is the interplay of induction[16] and deduction[17], and is central to the process of scientific discovery. Retroduction combines inductive and deductive strategies to capitalise on their strengths and minimise their weaknesses, creating a cyclic process allowing movement between theorising and doing empirical research using both forms of reasoning. The process of constructing representations from the interaction between analytic frames and images involves retroduction.

Whilst the deductive-versus-inductive research distinction is a simple differentiation, most research includes elements of both, for example it is impossible to do research without some initial ideas, so almost all research has at least an element of deduction, and almost all research can be used to advance theory in some way (i.e. it has inductive qualities). In other words research involves retroduction because there is a dialogue of ideas and evidence (Ragin 1994). Insights into the possibility of more radical solutions or improvements are offered by multidisciplinary approaches as evidenced by Kuhn (1962).

Simply stated the research method used for this thesis is the attempt of an engineer to move closer toward a more holistic approach in order to gain from perspectives on paradigms and the use of those reflections in seeking solutions to the stated problems.

Relevant theory and frames; data and images

The relevant theories and issues from multidisciplinary perspectives are reviewed including those from the fields of engineering, ecology, economics, law and sociology. Industrial ecology, industrial symbiosis, environmental policy and law, life cycle assessment (LCA) and material efficiency are used as analytical frames. Evidence comes from materials characterisation, case studies, surveys and LCA modelling.

2.1.2 Multidisciplinary research

The specific focus of this research was developed from within a multidisciplinary research group which sought to approach the issue of achieving closure (including optimisation) of resource cycles via consideration of all the chemical, physical, technical, economic, legal, administrative, environmental, and social issues together in a systemic way. Part of this research was conducted under the research project Pro-environmental Product Planning in a Dynamic Operational Environment Now and in Future - Methods and Tools (ProDOE) which was funded as part of the Finnish Academy Research Programme on Sustainable Production and Products (KETJU 2006 - 2010) (ProDOE 2010). The group researched the complex interactions between the

[15] *Retroduction* - makes possible a research process that is characterised by the linking of evidence and theory in a continually evolving, dynamic process (Ragin 1994).

[16] *Induction* - an approach to enquiry that builds generalisations out of observations of specific events - starts with singular or particular statements and ends up with general or universal propositions - explanations based on facts gained from pure observation - nature will reveal itself to a passively receptive mind - criticised as essentially descriptive and with questionable disciplinary objectivity.

[17] *Deduction* - (or falsificationist) - approach is the reverse of an Inductive one - begins explicitly with a tentative hypothesis that forms a theory which could provide a possible answer or explanation for a particular problem, then proceeds to use observations to test the hypotheses - moves from a general or universal statement, to a conclusion that is a singular statement - forms a hierarchy from theoretical to observational; from abstract to concrete - observation is guided by the theory - criticised for lack of originating process for birth of hypotheses.

setting of regulatory objectives and the choice of scale of the engineered industrial ecosystems to be regulated and managed as well as the complicated interconnections, dynamics and relevant cycle specific boundary conditions. The situation concerning two major Finnish process industries, namely the metal and fibre cycles was the focus for these studies. The ProDOE research process allowed group members to draw on the synergies of multidisciplinary work to create an interdisciplinary research environment.

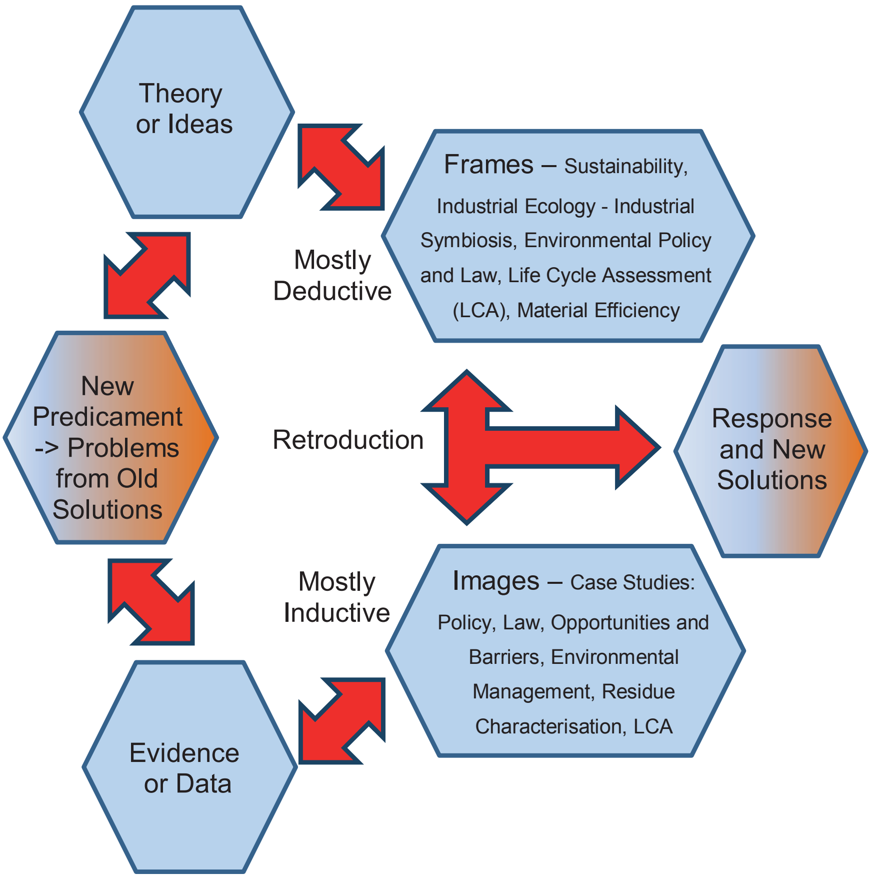

Figure 6 *Research model based on theory and empirical data (modified from Ragin 1994)*

It is the valuable experience from that process that helped to inform this research approach and methodology.

2.1.3 The Bothnian Arc region

The Bothnian Arc around the northern gulf of the Baltic Sea is situated between Finland and Sweden and forms an industrial system with a large number of metals, paper and pulp mills and also fertiliser and fine chemicals production (Annex 1). The environment in the area is fragile and needs a careful strategy to balance the ecological and economic drivers and impacts in the region (Donnelly et al. 2005; Heino et al. 2008). The primary metals and forestry products industries have a large footprint and hence an important role to play in the environmental quality of the area. New policies and technologies need to be designed to minimise the ecological impact of these industries without losing the economic incentive to support the livelihood of communities in the area (Wierink et al. 2010).

Some of the process industry companies in this area are actively attempting to minimise their wastes and increase material efficiency by developing new products from their production residues and wastes. The active research into the opportunities of residue-based symbiotic product development between two of the largest industries in this area, namely the steel, pulp and paper industries and assessment of the performance of such symbiosis concepts is the main focus of this work.

2.2 Focus of research papers

The research papers included in this dissertation utilised a combination of approaches from a spectrum of subjects from convergent research concerning specific materials analysis, the use of survey data, life cycle assessment/modelling, to more divergent research relating to policy and legal review based on case studies (**Figure 7**). The detailed descriptions of materials and methods are included in each individual paper which because of their wide scope and variance are not repeated here for each case. The theoretical basis for these approaches and any issues with them are outlined in Section 3 Theoretical background.

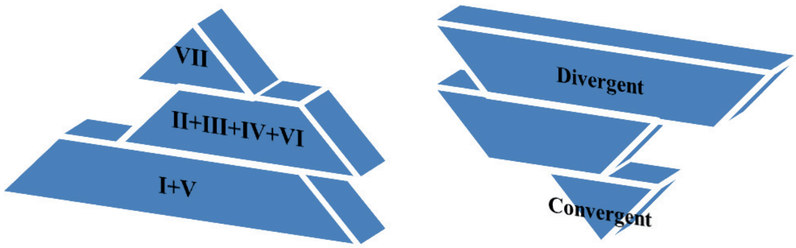

***Figure** 7 Contribution and perspective of publications in this thesis*

Symbiosis product concepts and selected process industry residue streams outlined in **Paper I** are examined in **Paper V.** A traditional experimental approach to materials characterisation studies is used in order to report on their physicochemical properties and leaching behaviour, and assessing their performance in relation to legal limits set for their utilisation as land ameliorants and ameliorant product concepts. Each individual paper sets out the specific sampling and experimental approaches adopted in each case. In **Paper VI** symbiosis product concepts described in **Papers III** and **IV** are assessed on a life cycle assessment basis to determine the environmental performance of manufacturing of potential symbiosis based on secondary raw materials compared to manufacturing of similar primary products, and on an exergy assessment basis to determine the resource use efficiency of the selected production. **Papers IV** and **VII** also include surveys of industrial actors.

Papers II, III, IV, V, VI and **VII** all included assessment of legal issues related to residue utilisation with **Papers II, III, IV** and **VII** in particular focussing on higher level policy aspects concerning the highest level drivers and barriers to improved residue utilisation.

The synthesis of the findings in these papers is developed in this work via an in-depth results and discussion section.

3 Theoretical background

In order to more effectively advance some of the arguments in this work some of the broad context to the economy-environment relationship in terms of sustainability needs to be outlined. In addition, the development and progress of the *industrial symbiosis* (IS) and *industrial ecology* (IE) field, its application to the target industries, as well as the questions, tensions and unresolved issues that arise out of the institutional frameworks within the EU are provided as background. Other institutional dimensions such as the many approaches, methods, tools and principles that have been used in attempting to address different problems in the fields of waste management and resource efficiency also have a bearing here. Many of the aspects illustrated in **Figure 8** describing a so-called 'whole system' approach are recruited to describe the problem space. This approach is one of redesigning resource flows to minimise harmful emissions and waste of resources and acts as a unifying concept for a range of measures aimed at eliminating waste and challenging old ways of thinking.

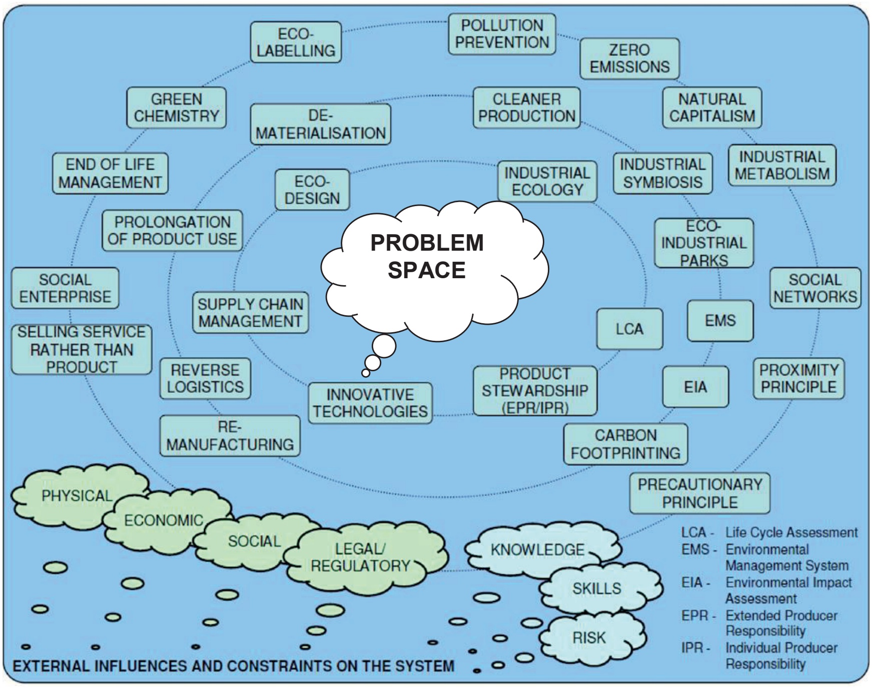

Figure 8 *Problem space for addressing opportunities and barriers to residue utilisation (modified from Curran and Williams 2012)*

Given the depth of these themes this section explores additional ground to that presented in the published articles, which by their nature are depth constrained. Furthermore, the design of this theoretical framework was partly driven by the fact that previous studies have not usually placed discussion of material efficiency and institutional aspects within broader frameworks such as those of broad environmental sustainability and the use, meaning and value of ecological metaphors for industrial production. Therefore the approach adopted to these topics was through a holistic, comprehensive, multidisciplinary and integrated framework. The underlying idea was to provide a broader perspective to these key concepts more amenable to interdisciplinary discourse.

3.1 Sustainability in the environment and society

Concerns over environmental limits such as the Club of Rome's seminal 'Limits to Growth' report (Meadows et al. 1972) concerning the challenge of environmental sustainability in the face of growth, have led to a new Neo-Malthusian[18] phase of concern over energy resources and climate change with a backdrop of severe global economic problems. Put simply, a possible global population of 9 billion people by the year 2050 enjoying the same standard of living as the Western world will require an economy 15 times larger than the global economy in 2009 (UK Sustainable Development Commission 2009). That this hardly seems possible highlights recent moves to begin to acknowledge our strict and ultimate dependency on limited natural resources and sensitive systems and to organise our developmental systems to take account of, and slow down, environmental degradation caused by our activities. These concerns have been encouraged by immediate resource scarcity issues relating to access to energy, water resources and other threats such as climate change (IPCC 2007; UN 2005). We have now started to see new ways of considering nature, its capacities and vulnerabilities, via the emergence of a new idea for human development - *sustainable development*. This has placed the natural environment clearly at the centre of a qualitative world vision that emphasises the environment's critical role in supporting the viability of long term human development and seeks options for more effective relationships between natural and human systems both physically, spatially and temporally (WCED 1987). Sustainable development is therefore part of efforts to integrate environmental, economic and social considerations into a new development paradigm characterised by dynamic processes, normative aspects and steering of change (Baker 2006).

The interdependence of resource utilisation, social progress and environmental impacts, conflicts between the economy and natural systems and their tangible effects, are now beginning to be measured. The increasingly stressed relationship between the environment and highly expansive economic development trajectories are no longer in doubt and issues brought about by the current economic system are beginning to be questioned within the context of sustainability (UN 1992). However, the current mainstream sustainable development (SD) concept varies little from a *business-as-usual* (BAU) assumption. The issue in question is described by a very simple thesis: that economic growth, which viewed from the point of view of economics, physics, chemistry and technology has no discernible limit, must necessarily run into decisive bottlenecks when viewed from the point of view of the environmental sciences (Schumacher 1973).

Part of the problem has been identified by some as a lack of definition of the term *sustainable* or even that of *development* (Ehrenfeld 2008). In other words an explanation or agreement on what we mean exactly by 'sustainable' and what 'development' encompasses is missing in the discourse. Are we looking at strict planetary systems sustainability? Is the idea of development really captured by rough measures such as Gross Domestic Product (GDP)[19] or do metrics need to take account of quality in human systems? (Ehrenfeld 2008). A strict definition of sustainability can be found in the 4 Sustainability Principles (Robèrt et al. 2002), otherwise known as The

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[18] *Neo-Malthusian* - concern with the sustainability of growth, originally predicated on Malthusian population concerns but latterly neo-Malthusian with respect to concerns over resource depletion and environmental degradation.

[19] *GDP* - the monetary value of all the finished goods and services produced within a country's borders over a specific time period.

Natural Step (TNS) Principles. These determine the outcome of the process of sustainable development in a sustainable society as one where nature is not subject to systematically increasing: 1) concentrations of substances extracted from the Earth's crust, 2) concentrations of substances produced by society, or 3) degradation by physical means; and in society 4) people are not subject to conditions that systematically undermine their capacity to meet their human needs. However, it can hardly be said that this is what we mean by sustainability in its normal sense and the term is used to cover many shades of the concept from true bio-physical sustainability to a form of reduced 'unsustainability'.

The economic system is a rapidly growing and materially open subsystem of the larger parent global ecosystem, which is non-growing and materially closed (Korhonen 2008; Daly 1990). Industrial society still depends on large, continuous and growing inputs of fossil fuels for the provision of food, goods and services in order to function (Korhonen 2006). The *full-world* metaphor as espoused by Daly (1996) and Costanza et al. (1998) has as its message the idea that the modern world view has been unsuccessful in terms of sustainable development [i.e. a failure of modernity's neoclassical economic paradigm (Ehrenfeld 1997) through its normative influence on western industrial society to acknowledge that the human economic system is only a subsystem of the planetary ecosystem (Korhonen 2006)]. The full world metaphor argues that the world has become full of human-manufactured capital in the form of our economic system, infrastructure and goods, and on the other hand empty of natural capital, in the form of natural resources, energy, raw materials and the depletion of capacities such as sinks for emissions and biodiversity. This contrasts sharply with the *empty world* that pertained prior to industrialisation, where investment in human-manufactured capital for economic development had huge immediate utility and enabled much needed progress to be made in terms of improving human conditions. The message of the full world metaphor is therefore that natural capital is the new limiting factor of economic development.

The implication that flows from this is that conflict between the human economic subsystem and the parent ecosystem means that sustaining an economic system predicated on growth is unsustainable and ultimately impossible within finite ecosystem boundaries. Financial analogies for the operation of renewable and non-renewable natural capital can also be suggested. Here, in simple economic terms, renewable capital should be treated as the basis of 'income' and non-renewable resources as capital assets or 'savings'. In this view income needs to be 'earned' from renewable sources and scarce capital assets not consumed for day-to-day living, but rather saved or used for 'investment' in the creation of further income generating infrastructure. Again the appeal and power of this analogy rooted in ordinary economics is clear. This analogy is put succinctly by the ecological economist Schumacher (1973) who said 'A businessman would not consider a firm to have solved its problems of production and to have achieved viability if he saw that it was rapidly consuming its capital.'

The explosion in the evolutionary speed of human development and expansion has not needed to equilibrate with natural systems, before now, due to the creation of a meta-environment via technology and readily available fossil fuels and other resources not imposing severe limits on growth. We exist in a meta-environment leveraged out of cheap energy, a temporally displaced Type II ecosystem with a costly (on energy terms) inorganic technosphere to support us (**Figure 9**). After all, on the widest scale, we live in a Type III system (the whole Earth system), a system that will always be a Type III system. However, we temporarily found ourselves in a Type I ecosystem during the Industrial Revolution with its exploitation of new land and resources through technological leverage of almost free energy and ostensibly limitless environmental sinks. We are now moving towards a more constrained Type I system levered out of readily available fossil fuels (still essentially free in an ecological sense) but about to be demoted (or perhaps we should say reminded) that it is at best a Type II ecosystem that can only be maintained via the husbanding of remaining resources and assimilative capacities or sinks (Allenby 1992).

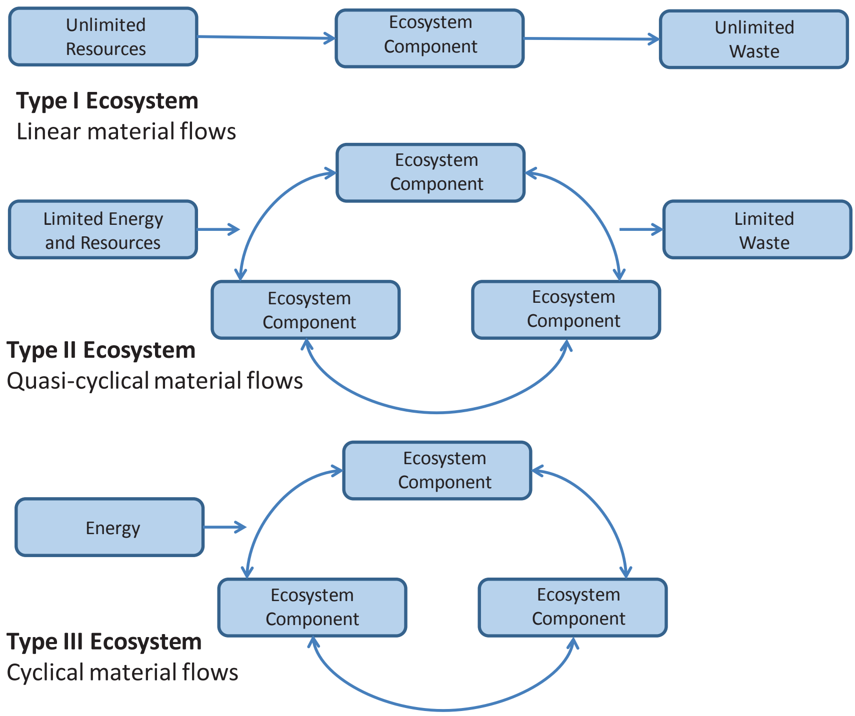

Figure 9 *System types (modified from Allenby 1992)*

Economic systems have extreme positive feedback attributes because they ensure more output can be leveraged via fossil energy use and the system is not strongly coupled to the underlying biophysical world in terms of communication of resource scarcity and environmental degradation in the form of feedback or balance signals over any sensible timescale. The economy is essentially a surplus energy equation (Ayres 2004). Growth in output (and in the global population) since the Industrial Revolution has resulted from the harnessing of ever-greater quantities of energy. Society as we know it today is a product of the use of extraneous energy to leverage limited human physical capabilities and the effect of abundant extraneous energy alone permits the earth to support a current population of over seven billion (Jackson 2009). However continued easy access to energy leverage is now being questioned with concerns over maintaining energy production levels and increased costs of energy extraction and the severe economic effects this would cause (Morgan 2010). The current paradigm is one of *ever greater consumption of resources* which is in itself a driver of growth. If growth is indispensable to economic systems then according to Ayres (2008) '...in effect, a new engine of growth is needed, based on non-polluting energy sources and selling non-material services, not polluting products…'

Metabolisms work because there is an energy gain from all exchanges, the energy obtained is used for growth, expansion and reproduction. Commerce is similarly driven by surplus; where surpluses are traded using money as a metaphor for value. Basically, human nature, the market and nature all seek a yield from any form of activity and those that do not deliver such positive feedbacks are simply not successful and therefore not adopted or replicated (Gössling 2001). Therefore the functioning of the economy as a metabolism, a mere subset of the environment, is a paradigm change realisation that has profound implications for our social systems, their economic foundations and the question of how we should live. Writers such as Ayres (2004) have, however, cautioned against using direct ecosystem analogies for economic systems (as such) due to there being no 'markets' in the biosphere and no analogue for labour.

3.1.1 Sustainable development

Human temporal and spatial considerations have scaled up during human philosophical and industrial development. Our industrial culture has developed a long way from earlier simple utilitarian agricultural systems utilising organic materials with little waste, a clear chain of utility and institutional systems for addressing the risks of over exploitation of the local environment in some jurisdictions and cultural phases of human development, see *Tragedy of the Commons* (Hardin 1968). Traditional cultures have often developed effective cultural norms to deal with the husbanding of scarce resources (i.e. workable solutions to address over exploitation) unlike modern industrial societies whose economic model deals badly with addressing resource scarcity and the allocation of common pool resources (CPR). However, recent economics research (Ostrom 1990)[20], identifies key institutional factors that make CPR management more successful, including spatial/local dependence on a particular CPR and sensibility of the immediate threats to its sustainability.

The ever-increasing demand for natural resources for consumption, are generating a cumulative strain on the natural environment, our living conditions and surroundings. The early policy prescription of exploitation of the environment and economic growth at all costs, as an axiom, has enabled the application of reductive science and technologies to the conversion of natural resources and has led to unprecedented advances in human health and material wealth. However, this progress has also led to the assumption of limitless resources now built into our linear consumption behaviour, our prevailing economic thinking and our institutions at a fundamental level. As such, our critical and absolute dependency on the ability of the biosphere to continue to provide services such as water and air purification, food and fibres, waste sinks and materials cycling, and the need to ensure that these services are not being degraded beyond a level at which their capacity can no longer support our subsistence and development, is not reflected in our economic behaviour.

3.1.2 Ecological economics

The current inability of our economy to fully price these natural services or to develop alternative systems that support human development and progress by acting in synergy with the environment, mean that our current linear approach is seriously over-drawn in terms of its sustainability (Everard 2005). Our limitations and inability to solve this unsustainable situation from within the current dominant paradigm of science out of modernity[21], has reductionism at its core in that it concentrates on single systems components and largely ignores the wider system and systemic interdependencies involved. According to Korhonen (2008), if ideas such as eco-efficiency that accept the

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[20] Elinor Ostrom - Winner of Sveriges Riksbank Prize 2009 in Economic Sciences in Memory of Alfred Nobel.

[21] *Modernity* - in this sense the social relations associated with industrialisation and the myth of progress.

economic science paradigm as the dominant one, are technocratic, relying on economics, engineering, and business economics as sources of theory, then consideration of social and cultural issues and context in different regions is missing. In this sense, modernity has not tended to help in the elucidation of any systemic common sense or intuitive theme arising from multidisciplinary fields therefore. An environmental protection example often given to illustrate this reductionist tendency is that of having focussed on fossil fuel pollution's acidic combustion products in the past (i.e. the direct polluting effects of SO_2 and NO_x) and having overlooked the climate change effects of fossil fuel combustion's CO_2 emissions until only recently (Hueseman 2001).

Plainly stated and as pointed out by numerous ecological economists (Jackson 2009; Costanza et al. 1998; Daly 1972; Schumacher 1973), the current economic paradigm is blind to the limitations of the material world and we have an inability to regulate financial markets which makes us unable to protect natural resources and curtail ecological damage. In effect, to continue to achieve economic growth we have taken on unsustainable ecological liabilities. Human capabilities are therefore bounded on the scale of global population and a finite planetary ecology. The *axiom of economic growth* and how it is related to the size or throughput of the system generating it (the metabolic flow of matter and energy through the economic system) is not fully understood. How big is the throughput compared to natural systems and cycles? The question of how large the economic system can get is therefore critical, with the importance of this question now the subject of current empirical experimentation (and one that we are all party to since we are no longer mere 'observers' of this particular experiment, but rather its subject matter.) Clearly, the current paradigm is one of sustained economic development (the expectancy of growth or expansion) and not one of sustainable development (one of viable continuity into the future.) The environmental ethic is therefore difficult to reconcile with any economic model either past or present according to Pearce et al. (1989).

3.1.3 Eco-efficiency

The concept of ecological efficiency or eco-efficiency has inspired policy makers reflecting the transition from *end-of-pipe* pollution control to product-orientated solutions. This approach looks to reduce the material and energy intensity of industrial production and products through dematerialisation and hence aims at functional decoupling[22] of the industrial economy from the natural one, i.e. decoupling a growing economy from its ecological impacts (Hukkinen 2001). Eco-efficiency is in line with the so called *win-win* vision of the economy and environment (Porter and van der Linde 1996). However, a criticism of this approach is that it is not useful or realistic on an environment-wide scale as it assumes system growth, expansion and economic BAU with any nominal impact reduction gains ultimately overwhelmed by continued system growth in a process termed *rebound* (Berg and Hukkinen 2011). Indeed, it has been claimed in some quarters that it is in line with the prevailing economic growth ideology of the global market economy and that instead of seeing environmental protection as a burden on the economy, it is even seen as a potential source of future growth (Cohen 1997). In fact, relative decoupling[23] (doing more with less) is only usually a temporary improvement in terms of environmental impacts since efficiencies will need to keep pace with the growth of a particular industrial sector or whole economies in order for

[22] *Decoupling* - refers to the amount of materials in relation to economic output or in relation to environmental impact.
[23] Relative decoupling - means that resource use or environmental impact is growing more slowly than economic output, i.e. they decline relative to GDP.

absolute impacts to stay at the same level. There is recent evidence that progress towards achieving relative decoupling by reducing the ecological intensity per unit of economic output has been achieved as a world-wide average (Dittrich and SERI, 2012). However, even if great gains have been made in relative decoupling over the last several decades, these gains have been entirely swamped by economic growth. For example, carbon dioxide emissions per unit of economic output have decreased, but growth in economic output has led to higher absolute emissions of carbon dioxide despite this increasing efficiency. To achieve a sustainable economy absolute decoupling[24] is needed, a situation in which resource impacts decline overall. Indeed, several developed, low growth, import dependant consumer-based economies that appear to have achieved a marginal level of absolute decoupling (e.g. Canada, Italy, Japan, Germany and the UK) may have simply 'exported' their impacts (i.e. displaced their raw materials consumption and related impacts to other countries by importation of goods or outsourcing of material intensive production on becoming more services orientated after the decline of indigenous heavy industries and manufacturing). However, it is important to note that such embodied environmental impacts (i.e. dislocations of environmental pressures through trade.) are not covered by direct material consumption (DMC) figures) (Dittrich and SERI 2012).

Eco-efficiency efforts have however formed the main response to addressing sustainability issues so far, where reduced environmental impact risk and materials and energy efficiencies are sought through seeking to do more with less. Concepts such as eco-efficiency are useful however in small systems to focus on local efficiencies. The concept appeals to those seeking incremental and continuous change, in other words the sort of economic growth that can be achieved whilst simultaneously protecting the environment (Bluhdorn 2000). The idea may also seem much easier to adopt as part of the immediate business strategy than other more radical or unfamiliar environmental concepts (Korhonen 2008). This approach is operationalised in indicators such as ecological rucksack (mass of natural resources used in product production), ecological footprint (land area used to provide services), MIPS (material input per unit of service) and Factors 4 and 10 (expressions of quantitative targets with time schedules for dematerialisation). Eco-efficiency has also resulted in the development of tools such as life cycle assessment and management for products and product systems, as well as the extension of this thinking into wider systems involving more actors such as in the concept of industrial symbiosis (IS).

However, eco-efficiency can be used as a practical tool to assist or measure actions and success of policy programmes, if not as a vision, or objective in itself for achieving sustainability.

Eco-efficiency and lack of a supporting sustainability narrative

The effect of the lack of a viable alternative narrative to the economic growth story for a truly sustainable system as highlighted by Hukkinen (2011), is a major obstacle to paradigm change which is described as the highest leverage point in any system (Meadows 2008). Any alternative way forward would need narrative development to avoid the *non-story* situation of current approaches, which, although critical of the effects of the growth story still support and strengthen the dominant story or status quo, in other words a continuation of BAU by failing to offer an alternative (Roe 1994). Such BAU does include attempts to achieve short duration efficiencies, by the application of eco-efficiency ideas for example, but these are then swallowed by the rebound effect

[24] *Absolute decoupling* - refers to a decrease in resource use or environmental impact in absolute terms, i.e. they decrease overall as GDP increases.

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(Berg and Hukkinen 2011). However efficiencies do have a role to play in economic sustainability. Businesses are good at seeking such efficiencies that can reduce emissions and improve resource efficiencies which equates to being (at least) less unsustainable. However there is no alternative narrative available that gives a consistent vision of an economy founded on continual growth that delivers absolute decoupling from environmental degradation. It is claimed by some that there is a need for a different kind of economic structure or approach that suits an ecologically constrained world (Jackson 2009). BAU is in this respect is a reflection of our choice to concern ourselves with tangential or small and relatively irrelevant issues rather than deal with the looming big one.

Approaches to sustainability such as Natural Capitalism (Hawken et al. 1999) is often mentioned in terms of what could be achieved with resource productivity, however, once more the rebound effect means this only gives us more time to move to sustainable systems. Indeed, Adam (1995) has observed that it may not so much be a case of running out of resources but instead of running out of time. For example there will still be lots of fossil fuels and other minerals that can be obtained well after the current economic system or model becomes more difficult due to the availability of only lower grade resources and hence lower returns in the future (e.g. in the case of fossil fuels such as oil - the approach of zero EROEI[25]). A further metaphor linking nature to economics has also been suggested by some such that the whole *investment ecology* of our approach needs to be assessed because there is nothing in our culture's economic experience that illuminates idea of true sustainability (Jackson 2009). In other words we have only consumed natural capital so far.

The trap of the legitimacy of scientific rationalism possibly leading to substantive change being deferred through a reformist approach (i.e. BAU, marginally increasing environmental carrying capacity through eco-efficiency and thus buying time) is pointed out by Wells (2006). He further points out that to lay claim to scientific rationality in order to be an agent of change in the contemporary world may be insufficient because IE involves inevitable value judgements and is therefore ultimately political. The current focus on detail, measurement and models of *what is*, is not being balanced by enough application of these ideas to forward-looking aspects to speculate as to that which *could be* (in other words, bringing the lacking cultural, social and overall human dimension into the methodologies applied.) (Deutz at al. 2007). The current lack of a wider social narrative to support refocusing of effort on true leverage points for moving towards sustainability has also been a subject of intense research of late; cf. Berg and Hukkinen (2011).

These subjects are revisited in discussion of the role and value of ecological metaphors in Section 4.

3.2 Industrial ecology and industrial symbiosis

Systemic approaches to the management and utilisation of resources contributes to the process of sustainable development and to increased sustainability of all operations through more integrated and strategic management planning covering the full life-cycle perspective (Brady 2005; Kiely 1998).

Applying a systemic approach, such as that offered by *industrial ecology* (IE) which covers sustainability and recycling to achieve more sustainable systems, appears to offer

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[25] *Energy Return on Energy Invested* - zero EROEI means that if one unit of energy is needed to extract and utilise one further unit of energy there is a zero net benefit.

a way forward. The broad cross-industrial approach that IE adopts in treating industrial systems as ecosystems includes networks of processes and material streams encompassing industry's wider links to society. IE aims at promoting sustainable development through creating adaptable and responsive approaches (Graedel and Allenby 2010) and the wide IE scale comprises broad normative, political and socio-economic elements (Chertow 2007). Further, the ideas involved in the allied idea of *industrial symbiosis* (IS) are an integral part of the broader IE approach, where IS looks at the utilisation and interaction of streams and processes within a studied industrial ecosystem, for example the residue utilisation and recycling of inter-industry residues. In this respect the IS scale is focussed on engineering approaches (Chertow 2007).

The IE field is an emerging one that requires a combined approach from practitioners in the fields of environmental engineering and technology, corporate environmental management and environmental policy studies. The key metaphor of IE is the natural ecosystem, one driven by solar energy and consisting of harmonised material cycles and energy flows. It is easy to see how an IE predicated cyclical system differs greatly from the linear and wasteful material and energy flows characteristic of typical production systems in current industrial societies heavily reliant on non-renewable fuels. In effect, *IE thinking* encourages consideration of the utilisation of production residuals as new raw materials throughout production and consumption chains, whilst ideally exploiting renewable sources of energy by way of analogy between our production processes and their wider system connections and those of natural biological web systems. These ideas therefore have the potential to conserve non-renewable resources and promote sustainable development.

The way in which the dominant environmental management concepts have developed from pollution control through to industrial ecology and sustainable development as interlinkages between environmental and temporal concerns as described by Baas (2005) are shown in **Figure 10**.

3.2.1 Industrial ecology

The idea of industrial ecology (IE) involves the discussion of the possibilities of, and opportunities and problems involved in, attempting to use the operation of natural biological systems as metaphors in the approach to the design, operation and decommissioning of industrial production systems in order to reduce their impact on the environment.

The idea has as its starting point the idea that some individual and most hierarchical carbon based biological systems utilise scarce resources in an optimal manner. This involves cycling materials and energy efficiently, so that the requirements for the maintenance of stable populations are satisfied and very little waste is produced. Despite natural ecosystems often being inefficient on a local scale in terms of material and energy use, their consideration on non-local scales can be considered as closed, for example the carbon cycle; see Harte et al. (2001). However, despite the fact that many organisms do consume some non-renewable minerals (non-renewable in the sense that they that can only be replaced by very slow geological processes) the argument is that, by and large, these materials are not consumed in the homeostatically regulated biosphere at a rate in excess of natural replacement levels. The cycling of these types of nutrients is necessary because there is no source of food for organisms outside the biosphere and the avid degradation of organic wastes and efficient re-assimilation or cycling of key minerals needed for life, such as phosphorous for example, is therefore due to its scarcity in nature and low availability from non-biological sources. These ideas therefore have their roots in ecological and systems thinking.

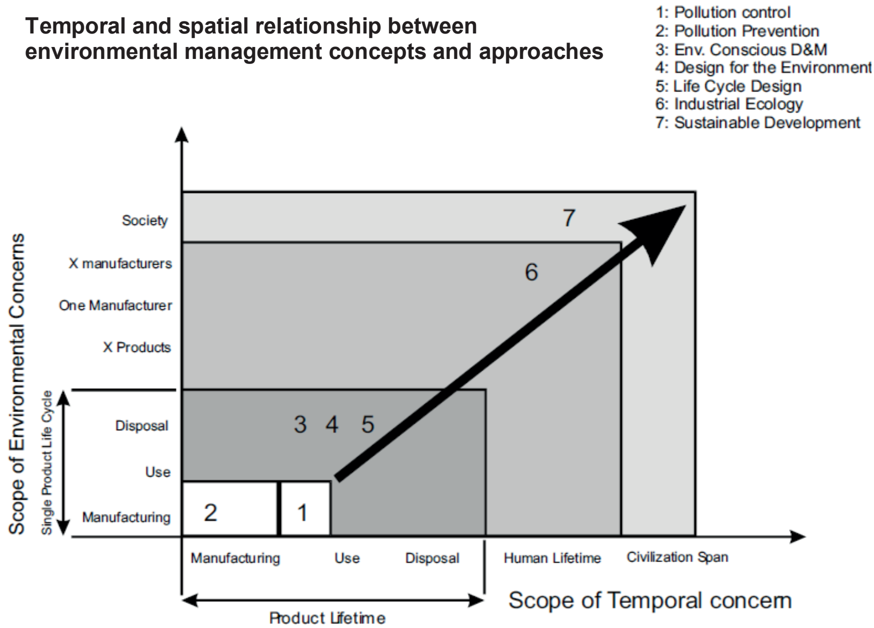

Figure 10 *Environmental management concepts as interlinkages between environmental and temporal concerns (modified from Baas 2005)*

From early ideas on industrial metabolism (Ayres 1989) that first partially described the IE analogy in terms of systems approaches in the case of manufacturing, the combination of the holistic approach with the biological metaphor was suggested by Frosch and Gallopoulos (1992) from where, building on other contributions (Erkman 1997) the etymology of the term *industrial ecology* can be traced as an organising principle for viewing certain industrial operations or sub systems as potential candidates for closure.

Such a systems view is an holistic approach that attempts to close a system, analogous to a natural ecosystem where residues from one industry can be used as raw materials for another. In such an industrial ecosystem, the consumption of energy and materials is optimised, waste generation is minimised, and the effluents from one process serve as the raw material for another (Frosch and Gallopoulos 1989). The IE concept goes beyond the traditional end-of-pipe thinking of waste management and pollution control and brings the ecosystem concept and its dynamics into industrial systems thinking (Yang and Lay 2004).

According to Graedel and Allenby (2003) IE has been defined as:

> *'The means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution […]; the concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them […]; a system view; in which one seeks to optimize the total material cycle from virgin material, to finished material, to product, to waste product, and to ultimate disposal […]; factors to be optimized include resources, energy and capital […].'*

Despite its historical focus on technology, this definition gives a good feel for the breadth of contextual factors involved, from the highest level of environmental services and also social constructions, through to the more concrete engineering aspects of sub-system goals. More recent focus on subsystems by Gallopoulos (2006) returns explanations of the metaphor's approach as an attempt to:

> '*link production and consumption/use subsystems into a seamless closed-cycle system where the output from one subsystem becomes the input for another.*'

Biological systems are generally considered to be cyclical, with materials and energy circulating between entities. Economic systems are, in contrast, typically linear – extracting materials from nature, wastefully utilising them, and then returning them to nature in a more or less unusable form (Korhonen 2005b). Nature already provides us with many ecological lessons on unsustainable behaviour of individual sub-systems and populations when temporarily afforded scarce resources in abundance and limited opportunities for connection or access to a wider web of ecosystem services in the form of waste and by-product handling. For example consider yeasts, a sobering model of ultimately finite growth potential due to dwindling resources and finite environmental waste sink capacity in terms of poisoning by waste products in a closed system (Wells 2006). However, a common objection to attempting the adoption of a *closed loop recycling economy* is the near impossibility of complete recycling (of a given material) given the prohibitively high financial and energetic costs and thus its *practical* impossibility (Gössling 2001). However, recycling usually involves *downcycling* or the cascading to use in, or as, a lower purity material or one with decreased usability. Under these circumstances the economically and ecologically justifiable level of recycling to further use could be assisted by using the concept of entropy production as a measure for the associated costs of production (Gössling 2001) and consumption (Connelly and Koshland 2001). The problem of the technosphere's inorganic material streams and the energy barriers to their recycling are therefore a key issue here.

The field of IE provides a comprehensive framework for studying the interactions between modern technological society and the environment (Harper and Graedel 2004). In general, IE with its systems basis can look at the interactions of our technological systems, its flows of materials and energy, with the wider environment, without too focussed an analysis of linear engineering sub-systems. The industrial IE metaphor is even applied to much wider systems and larger numbers of actors and complexity, even attempting to encompass whole industries or regional economies. It is often underlined that IE is an effort for implementing industrial sustainability through new industrial practice, to move production and consumption in society in a more ecologically inspired and environmentally acceptable direction. In this respect IE promotes the necessity for inter-disciplinary cooperation since solutions to complex problems raise difficult questions related to normative (political) and scientific issues that need discussion (Hermansen 2006). IE's ability to consider the influence of economic, political, regulatory and other social factors that impinge on the use, transformation and disposition of resources makes it a useful approach (Diwekar 2005). The usefulness of this ecological metaphor in attempting to draw analogies between ecosystems and industrial systems lies in its ability to look beyond the current situation and generate new ideas that can be used as sources of new principles, strategies and management tools and practices (Korhonen 2004b).

3.2.2 Industrial symbiosis

Industrial symbiosis (IS) is a central concept of industrial ecology (IE) and involves the detailed study of material and energy flows and exchanges between multiple actors in local industrial systems (**Figure 11**).

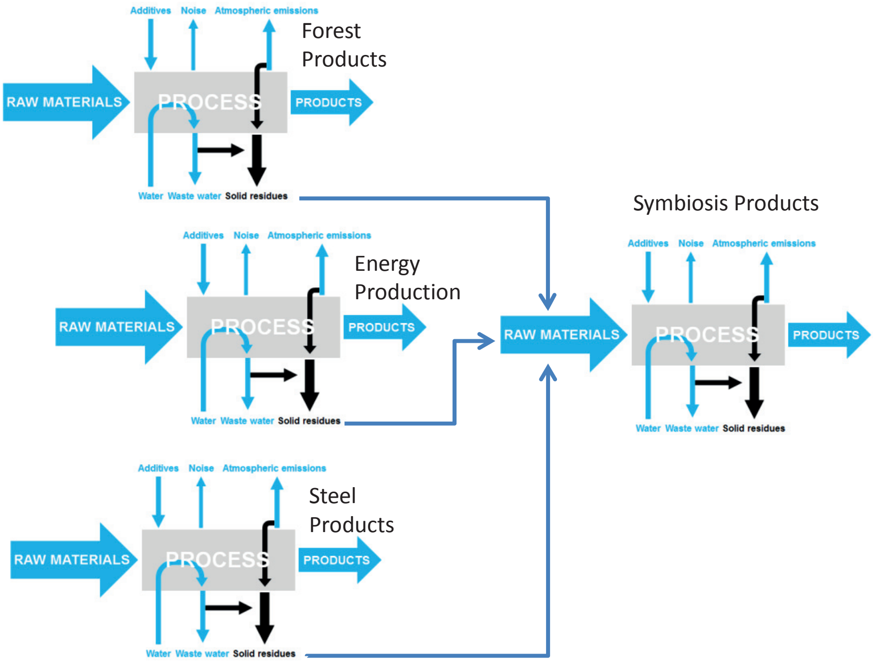

Figure 11 *Environmental burdens generated by unit processes and simple linear cascade of residue utilisations (modified from Dahl et al. 2008)*

The simple input-output model of economic exhanges involving natural materials and energy in, with goods, services and wastes out is augmented by attempts to link inputs and outputs between different actors and make use of as many outputs as possible. The IS idea appears to manifest itself on different local levels, be it the optimisation of a single process, a complex or an eco-industrial park, where different companies attempt to engage in industrial symbioses, described by Chertow (2000) as situations in which:

> *'traditionally separate industries form a collective to competitive advantage for the exchange of materials, energy, water and/or by-products.'*

Chertow (2007) has developed criteria for the definition of an IS in the form of an heuristic that requires at least three entities to be involved in exchanging at least two different materials, products or resources and for none of them to be primarily recycling-orientated businesses.

The example of Kalundborg, Denmark

A famous case of industrial ecology with embedded industrial symbioses is an industrial park in Kalundborg, Denmark. Individual industrial symbioses have sprung up over a period of 30 years around a central anchor tenant (a power station), such that the site's industries have developed into a complicated waste-reuse and energy recovery network that significantly reduces the use of virgin raw material (Grann 1997). Kalundborg has been used as a demonstration of a successful industrial ecology in 'designing' industrial systems to resemble natural ecosystems (Ehrenfeld and Gertler 1997; Frosch and Gallopoulos 1989), (**Figure 12**).

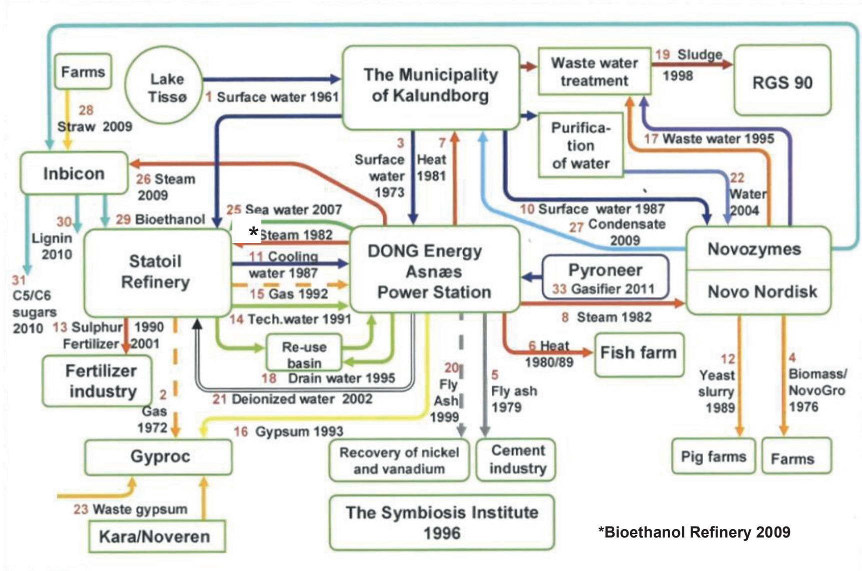

***Figure 12** Kalundborg industrial symbiosis - Denmark (modified from Lampindex 2013)*

It is not straightforward to define a scheme of system boundaries for IE and IS, and their differences in the discourse are hard to tease apart. It is not easy to capture this difference or where the transition from one approach to the other occurs except to emphasise IS as more amenable to a more deterministic engineering approach. In this sense IS deals with complicated, linear subsets of the existing human economy that could be said to ask: 'What is a possible solution?' whereas IE, which is a wider more complex and potentially normative idea, seems more to ask for a response to the question: 'What ought we to do?' In an attempt to simplify, we can say that IS therefore looks to the detail in subsystems generally and therefore less at the bigger picture, and conversely IE looks more to the big picture and less at the underlying physical basis and details. Studying the construction of an industrial subsystem and how to reduce its specific environmental impacts is squarely IS (i.e. tangible systems in defined space), whereas IE needs to take into account broader sustainability and therefore needs to be concerned with social factors and the incompatibility of a wider range of other factors that do not submit to easy analysis.

An IE vs. IS metaphor discussion in Section 4.4 below equates these approaches with linear vs. complex systems perspectives and links these starting points to the fields involved in environmental sustainability issues. Given that the broad IE approach and IS (as a part of the overall IE framework) focus on topics such as the overall operational environment and the creation of synergies between various local industrial systems (Chertow 2000; Heino 2006; Chertow 2007; Sokka et al. 2011a), industrial symbioses should be analysed and developed on a life cycle basis including comparison to standalone production (Lehtoranta et al. 2011).

3.3 IE and the Finnish forest and ferrous metals industries

The forest industry provides a useful example of an industry that generally resembles a pseudo (non-closed) ecological web, being fortunate as it is, in its reliance on wholly renewable raw materials (natural fibres that can potentially be produced in a sustainable way) and the fact that these renewable fibre containing raw materials also satisfy the main production process' feed stock needs as well as serving as the main energy source for power and heat production (this is discussed further in Section 4.2.3 in relation sustainability management and competitive advantage.) With the good fortune of the main raw material also doubling as the main process fuel, energy use within Finland's forest industry provides an interesting example of how the principles of industrial ecology can be applied in practice. Statistics show that around 70% of the fuels used within Finland's forest industry sector consist of local renewable wood-based or biomass fuels derived from within the forest industry itself, with around 95% of these fuels being used in the co-production of heat and power, and the residual energy produced during electricity generation utilised for industrial process steam or for district heating purposes (FFIF 2012). The industry is also the largest producer of wood energy and bio-energy in Finland and accounts for about 80% of the bio-energy production and consumption in the country. Some 40% of the wood raw material input to the industry is used to generate energy in different process phases (FFIF 2012).

Pulp and paper mill installations are therefore interesting systems to look at in terms of the opportunities for industrial symbioses and ecologies, since many mills have evolved into diverse network of co-operating firms and industrial units over recent decades. This type of system with its locally concentrated partnerships is an example of the kinds of symbioses seen in natural ecosystems, and has been described as an industrial ecosystem by researchers (Korhonen and Snäkin 2005). A Finnish mill site commissioned in the early twentieth-century would often have been a pulp mill and a paper mill with a hydropower plant arrangement and with the mills unconnected to each other (apart from the raw pulp supply), but having evolved into a much more integrated installation over recent times (**Figure 13**) (Pakarinen et al. 2010).

Pulp and paper mills generate a wide range and quantity of residual materials such as ash from energy production (e.g. such as from fluidised bed boilers), biosludge and paper mill sludge from wastewater treatment plants, rejects, fibre and paste suspensions from paper machines as well as lime waste, green liquor dregs and slaker grits arising from the chemical recovery process of the pulp mill (Monte et al. 2009). Also, quite apart from the additional mill site partnership processes, new in-plant activities have been developed at mills over recent years in response to the mounting pressure from residue management costs (**Figure 14**).

The management of solid wastes such as slaker grits and green liquor dregs derived from the chemical recovery cycle of the Kraft (sulphate) pulping process, as well as ashes and other residues has also traditionally been via landfilling. However, the rise in the costs of landfill, as a waste management option driven by regulation designed to protect human health and the environment, has led to problems in acquiring new sites for disposal purposes and has increased costs for their development and operation, such that solid waste generation represents a continuing disposal problem for the forest industry.

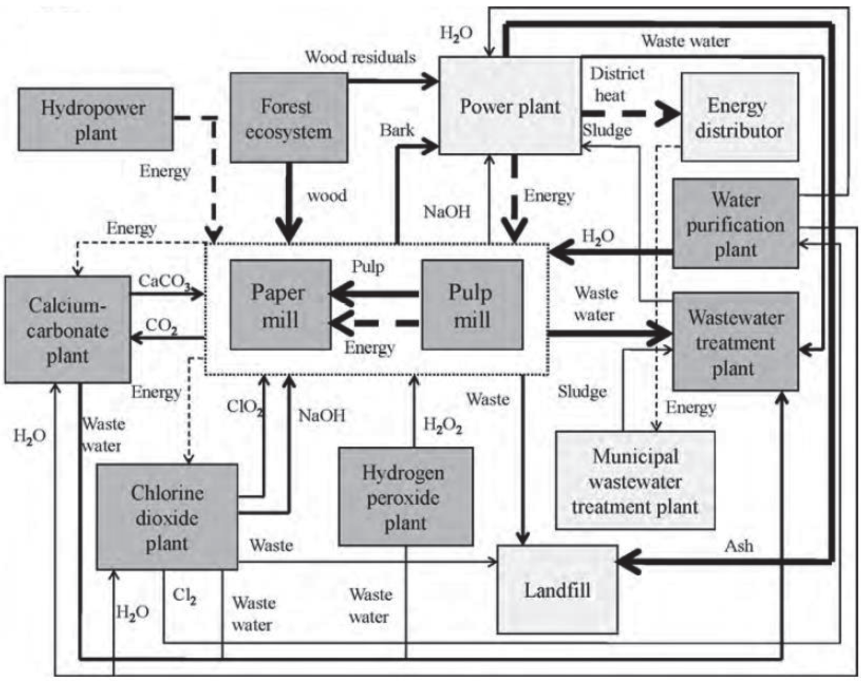

Figure 13 *Evolution of mill symbioses (Pakarinen et al. 2010)*

There is therefore a growing trend towards seeking alternative options for the utilisation of solid wastes in the Finnish pulp and paper industry. With concerted efforts to further utilise residues, it has been shown that the solid wastes arising for disposal can be decreased by more than 80% (Nurmesniemi 2007).

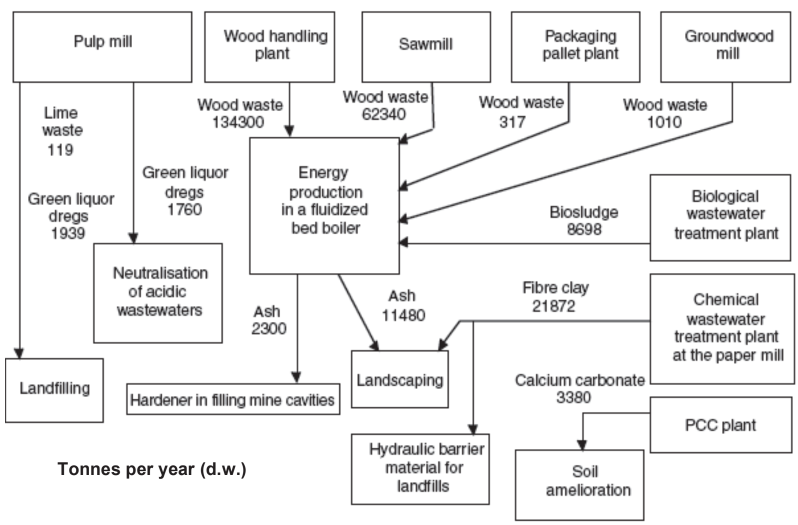

Figure 14 *Residue formation and utilisation at an integrated Finnish pulp and paper mill (modified from Nurmesniemi et al. 2007)*

The pulp and paper industry is clearly a highly energy-intensive industry. Due to the high demand for energy in its processes, most of the energy is produced by combustion of all the appropriate burnable residues available such as black liquor from the pulp-making process, clean wood residues (such as forest residues, bark, wood chips and sawdust), residues from wood harvesting, handling plant, sawmill and ground-wood mills, as well as biosludge from activated sludge plant (Cavrilescu 2008; Monte et al. 2009). The thermal energy generation from these types of industrial residues is a sustainable, more environmental friendly alternative to other fossil fuel based energy production processes as it significantly reduces the use of non-renewable fuels such as heavy fuel oil. In addition, the use of wood for energy production has a number of advantages over other fossil fuel based sources - it is domestic and usually local fuel, the handling of which creates jobs and promotes siviculture. In addition, the extraction of forest residues from the harvesting chain for utilisation in energy production is already common practice in Finland, providing an extra source of income for forest owners and having a positive effect on the economic viability of forest operations (Röser et al. 2006) and positive impact on regional and local development opportunities (EC 2009b). Furthermore, and perhaps critically, in the face of the global challenges of energy security and climate change, the generation of energy from local forest residues is potentially more sustainable and environmentally friendly. The use of wood residues as fuel therefore, allows the utilisation of renewable, natural raw material as an energy source without having any marked effects on the carbon balance of the wider ecosystem (Pingroud and Lehtilä 1997). Indeed within the EU, wood and waste wood continues to make the largest contribution to the share of energy from renewable sources in gross final energy consumption and the EU's 20% target for the overall share of energy from renewable sources by 2020 as outlined in the European Commission (EC) Directive on the promotion of the use of energy from renewable sources (2009/28/EC) (EC 2009b) means that these fuels will figure increasingly in future. However, a disadvantage of the incineration such residues is that they produce large amounts of ashes, and in the case of bubbling fluidised bed boilers (BFB), a residual bed sand material.

This work also includes consideration of residues from the ferrous metals industry, which unlike the forest sector, is an example of an inherently unsustainable process industry with its heavy reliance on large quantities of non-renewable fossil fuels, mineral ore raw materials and additives. However, existing ecologies in this industry are difficult to identify apart from examples where steel mills attract in-situ lime kilns and slag residue milling operations and some recent ideas for common Nordic solution to steel making waste oxide residue management between multiple mills in the Bothnia Arc region. Here the possibilities of utilising zinc containing iron waste residues from three[26] steel plants located around the Baltic sea coastal area to be used as an iron raw material in a common treatment plant was first suggested by Samuelsson et al. (2001). A rotary hearth furnace (RHF) is a potential residue handling plant in this application where zinc evaporates and zinc concentrate can be separated from the gas phase (Reuter et al. 2005). The direct reduced iron (DRI) as a main product can then be fed either into a blast furnace or a basic oxygen furnace. When dusts, scales and sludge are processed in a separate treatment plant (to avoid dust/sludge/scale physical handling, processing and contamination issues at originating mills), the main advantage is the avoidance of primary steel production process disturbances at the plant (Pöyliö et al. 2002). In addition to residues as an iron raw material, such waste flows contain zinc, which can be utilised as a raw material in a zinc plant (Heino 2006; Heino et al. 2008). An industrial symbiosis model treating zinc containing iron waste residues consisting of six production units has been proposed consisting of carbon steel mills in Finland and Sweden, Boliden Kokkola Oy zinc plant in Finland or Boliden Rönnskär plant in Sweden and a new novel iron regeneration plant to be placed adjacent to any of the

[26] Originally four mills at the time of the original article (Samuelsson et al. 2001)

three[27] carbon steel plants (Salmi et al. 2011). Preliminary estimates have shown that an annual 160 kt of carbon steel mill waste, together with the 1 Mt of previously landfilled waste, is sufficient for the operation of such an RHF in the Gulf of Bothnia area (Larsson and Wedholm 2009).

3.4 Forest sector residue types, origin and current utilisations

The Finnish pulp and paper industry produced a total of 6.8 Mt of pulp and 10.7 Mt of paper and paperboard in 2012, of which over 2 Mt of pulp is subsequently exported as raw material (FFIF 2012). The pulp and paper industry generates a range of organic and inorganic solids and sludges as bulk residue streams. The characteristics of these residues are mainly dictated by the mill type, paper grade being produced, the raw materials used and the applied process techniques and desired paper properties (Monte et al. 2009).

Pulping is a process for separating out the individual fibres in wood chips, sawdusts or recycled fibre by chemical, semi-chemical, or mechanical methods. Chemical pulping of wood fibres is achieved via one of two processes, either the sulphate *Kraft* or the sulphite processes. In the dominant Kraft process, which is an alkaline process, the active chemicals are sodium hydroxide (NaOH) and sodium sulphide (Na_2S), whereas in the sulphite process, the active chemicals of the acid cooking liquor is hydrogen sulphite (HSO_3-). Since only two semi-chemical sulphite-type processes are practiced in Finland it is the nature of the Kraft (sulphate) pulping method that has relevance here in terms of its influence on the characteristics of residue streams generated within the chemical recovery circuit (**Figure 15**). In the Kraft process, the spent cooking chemical components are retained in the black liquor process stream which is then concentrated via evaporation before regeneration for further use in the pulping process. The causticising process is a part of the pulp mill's chemical recovery system, in which the cooking chemicals used in pulping are recovered. The main purpose of this process is to convert inactive sodium carbonate (Na_2CO_3) back into the active cooking chemical sodium hydroxide (NaOH) and to ensure that this conversion is at as high a rate as possible. This requires the addition of make-up chemicals such as sodium sulphate (Na_2SO_4) for the regeneration of sodium sulphide, which together with sodium carbonate (Na_2CO_3) formed during combustion in the soda recovery boiler, act as feedstock for the causticising reaction to generate fresh white liquor (NaOH and Na_2S). The causticising step also necessitates the production of CaO and its hydration to calcium hydroxide ($Ca(OH)_2$) for subsequent reactions with Na_2CO_3. This is carried out through the calcination of $CaCO_3$ in an integrated lime kiln (Järvensivu et al. 2001).

The recovery, recirculation and reuse of the various aqueous streams present in the Kraft process leads to the build-up of so called non-process elements (NPEs) consisting of non-reactive or insoluble elements such as potassium, magnesium, manganese, barium, iron, aluminium, copper, nickel, chromium and zinc, the majority of which are detrimental to the pulping, bleaching or recovery processes. These NPEs are introduced into the process in the fibre raw materials, (wood chips and sawdusts), the make-up chemicals and process water, as well as from the corrosion of process equipment. The accumulation of NPEs in the bleaching process in particular may result in scaling problems, degradation (stress corrosion cracking) and filtration failures, and they can also catalyse the decomposition of expensive bleaching chemicals thereby reducing bleaching efficiency and increasing costs (Jemaa et al. 1999). In addition, NPEs can cause general operational problems such as scale formation on washers and the plugging of process equipment; hence their control and regular removal is required.

[27] Originally four mills at the time of the original article by Salmi et al. (2011)

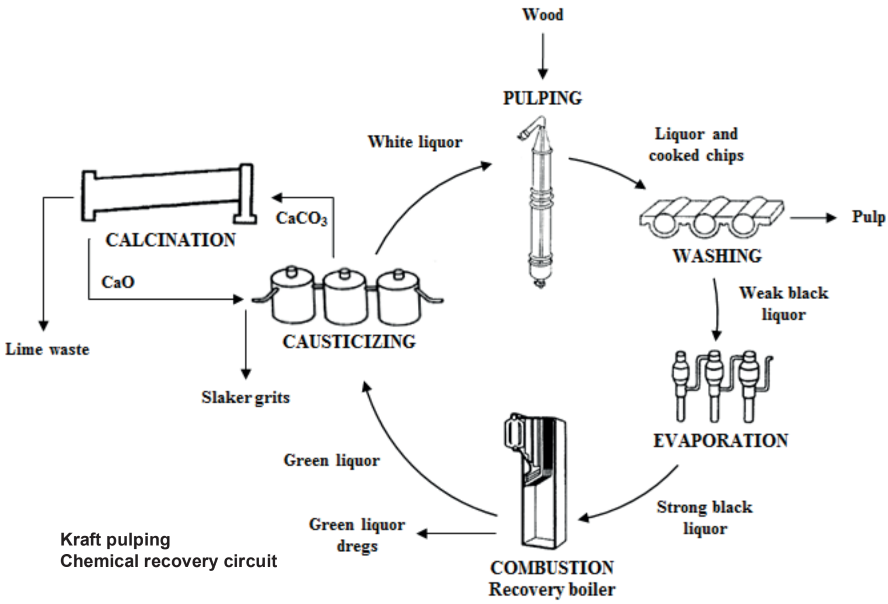

Figure 15 *Chemical recovery circuit of a pulp mill (modified from Järvensivu et al. 2001)*

As shown in **Figure 15** the combustion, causticising and calcination stages generate green liquor dregs, slaker grits and lime waste residues, which are then removed from the chemical recovery circuit in order to extract NPEs from the circulation (Martins et al. 2007). The purging of NPEs from the recovery cycle is via removal of green liquor dregs (from the main recovery cycle) and slaker grits (derived from the addition of make-up chemicals.)

The fact that the pulp and papermaking sector is highly energy-intensive industry with the additional characteristic of utilising significant quantities of water for facilitation of its process chemistry and the mechanical handling of raw materials and paper making fibre stock, significant quantities of incineration ashes and waste water treatment sludges are also produced. The incineration of wood residues, such as bark, wood chips and sawdust, and sludges as well as auxiliary fuels is undertaken in solid fuel boilers, which due to boiler operation and flue gas purification generate respective bottom and fly ash residues with differing characteristics. Combustion via BFB is a widely used combustion technology for energy recovery in the modern pulp and paper industry, and is especially suitable for inhomogeneous biofuels such as bark and other wood residues (Cavrilescu 2008). Ash residue fractions consist of bottom ash, that accumulates at the base of the fluidised bed boiler, and of fly ash collected from the flue gas by electrostatic precipitator (ESP), wet scrubbing, or mechanically via a multicyclone or a baghouse. Due to the fact that most of the heavy metals evaporate in the combustion process and condense on the surface of particulate matter (i.e. on fly ash) the different fly ash factions from an electrostatic precipitator's fields may have a different chemical and physical composition and are therefore variable in their suitability for subsequent types of utilisation with most of the inorganic nutrients and heavy metals being enriched in the fly ash (Dahl et al. 2009).

Other residues such as sludges are generated by the wastewater treatment processes at mills where primary mechanical clarification followed by secondary aerobic or anaerobic methods are used as a minimum. The treatment methods applied depend on the process generating the effluents and on its characteristics. Pulp mill effluents contain high levels of dissolved wood derived substances such as lignin, extracted during cooking and bleaching, hence, biological aerobic treatment is usually applied for these effluents. Chemical treatment methods are used in the case of paper and board mill effluents which also contain paper additives, such as kaolinite ($Al_2Si_2O_5(OH)_4$) and/or $CaCO_3$ (Kuokkanen et al. 2008). Other minor residue streams such as lime waste from integrated lime kilns are also generated periodically; this is a low moisture content mixture of partially and fully calcined minerals.

Indicative values for residues such as recovery cycle dregs, grits, lime wastes, ashes and waste water treatment sludge residues are given in **Table 1**.

Table 1 *Indicative residue generation (t a^{-1}) at a certain Finnish pulp and paper mill complex (Mäkelä 2012)*

Residue	**Green liquor dregs**	**Slaker grits**	**Lime waste**	**Fly ash**	**Bottom ash**	**Biosludge**	**Paper mill sludge**
Source process	Recovery boiler	Causticising	Lime kiln	Solid fuel boiler	Solid fuel boiler	Biological waste water treatment	Chemical waste water treatment
Generation[a] (d.w.[b])	3700	670	120	14,000	2600	8700	22,000

[a] Production capacity in 2004: 400 kt a^{-1} bleached soft- and hardwood pulp; 550 kt a^{-1} uncoated fine paper; 500 kt a^{-1} coated magazine paper (Northern Finland Environmental Permit Authority 2007)
[b] d.w. = dry weight
[c]Data from 2004 (Nurmesniemi et al. 2007)
[d]Data from 2008 (Nurmesniemi et al. 2010a, 2010b)
[c]Data from 2009 (Dahl et al. 2010)

The forest products industry creates some 140 kt of waste that is landfilled annually. Of this, about 20% is ashes and 40% green liquor dregs. The forest industry already utilises over 90% of its wastewater treatment plant sludge, fibre, paste and deinking sludge which are all utilised as raw material or incinerated, and about 85% of the ash generated is utilised in land construction and as fertiliser (FFIF 2012).

The utilisation of different process residues has long traditions in the Finnish forest industry. For example, ash from energy production is utilised as an amendment in earthwork constructions to improve soil strength or to reduce deformation and as a forest fertiliser (Mroueh et al. 2001; Mroueh and Wahlström 2002) or as a hardener in the filling of mine cavities (Nurmesniemi et al. 2007). Specific ash fractions and their suitability as forest fertilisers or as construction agents have also been under investigation by Manskinen (2013). Paper-mill sludge (that is also termed fibre clay), fibre and coating suspension, are increasingly being utilised in the hydraulic barrier layers of landfill sites´ containment systems (Kuokkanen et al. 2008), as well as in landfill construction (Mroueh and Wahlström 2002). Biosludge is typically incinerated in the pulp mill's recovery boiler or in the solid fuel boiler for energy recovery (Harila and Kivilinna 1999), and green liquor dregs can be utilised as an alternative neutralising agent for the treatment of acidic process influents to wastewater treatment plants (**Figure 14**) (Nurmesniemi et al. 2007; Pöykiö et al. 2007), as well as a potential soil conditioning agent (Manskinen 2013). However, slaker grits are still disposed of to landfill in Finland, although many researchers have reported beneficial uses for the residue such as in cement manufacturing (Castro et al. 2009; Gemelli et al. 2001), or as an alternative liming material to raise the pH of acidic soil (Cabral et al. 2008; Liard et al. 1999; Zambrano et al. 2007). Large quantities of fibre residues are also incinerated for energy recovery (Nurmesniemi et al. 2007).

3.5 Ferrous metals sector residue types, origin and current utilisations

The Finnish steel industry produced a total of 3.76 Mt of crude steel in 2012 (World Steel Association 2013). A typical large integrated steelworks such as the Raahe mill, northern Finland, can produce approximately 2.3 Mt of steel annually and gives rise to over 300 kt of mineral residues either directly utilised or stored for future utilisation. Such mineral residues have been used as a substitute for natural and raw materials in earthworks and road construction, soil improvement and industry (Ruukki 2012). The residual slags arising are by-products from the main processes of iron and steel smelting and their properties vary according to the types and characteristics of raw materials input and optimisation achieved in the manufacturing procedure. The possibilities for influencing slag properties at the time the slags are generated are generally limited by the relative importance of the primary products' properties over those of by-products and residues. To remove material impurities from liquid metal, a mineral fluxing agent is used to generate a separate residual slag phase that can separated from the metal product on a density basis. Other slag types are also generated at subsequent refining stages. The most important residues from crude iron and steel production include blast furnace slag[28], desulphurisation slag, converter steel slag and steel ladle slag (**Figure 16**).

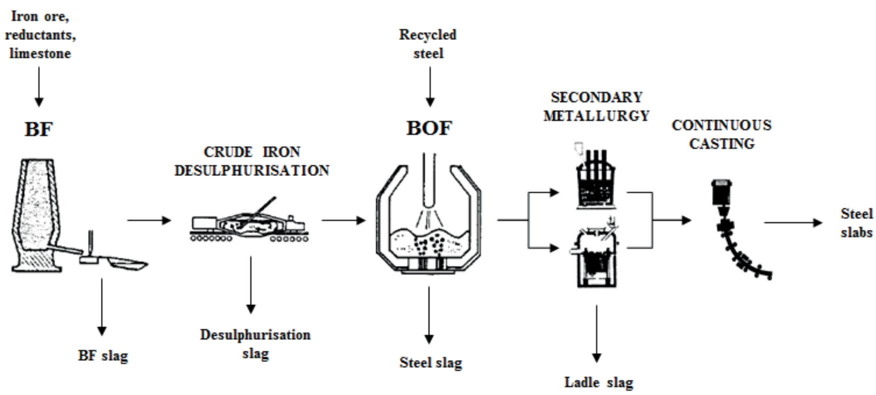

Figure 16 *Residual slag generation in integrated carbon steelmaking via the blast furnace/basic oxygen furnace process route (Mäkelä 2012)*

Blast furnace slag is a by-product of crude iron production from iron ore. In order to reduce iron ore to metallic iron, the blast furnace utilises coke and sinters or pellets, in addition to slag forming agents such as limestone flux. Blast furnace slag is generated as a by-product of simple chemical reduction. The molten slag is released from the furnace and rapidly quenched with large volumes of showered water which results in approximately 85% granulation. The process of cooling slag by granulation creates an

[28] *Blast furnace slag* - now determined not to be a waste but a by-product subsequent to EC guidance on distinguishing between wastes and by-products (EC 2007; JRC 2009).

amorphous material termed granulated blast furnace slag (GBFS) that lacks a regular crystalline structure, a characteristic that, in addition to its chemical composition has implications for its hydraulic properties and enables the grinding of such slag particles to a high fineness. GBFS from Raahe comprises mostly calcium oxide (CaO), silicon oxide (SiO_2), magnesium oxide (MgO) and aluminium oxide (Al_2O_3).

The hydraulic binding properties of ground GBFS means it is being used widely to replace a portion of Ordinary Portland Cement (OPC) in building products, and has been used as a liming agent in soil by mill operators (e.g. Ruukki Oy) as well as having been trialled as a solidification agent for wastes containing heavy metals (Savastano et al. 2001; Lampris et al. 2008). An average of approximately 300 to 800 kt of mineral residues will be produced annually by mill types the size of Raahe depending on the raw material feedstock. [Raahe has reduced slag generation since moving over to processed pellet feedstock instead of raw iron ore in 2012 (Ruukki 2012)]. In Finland, utilisation accomplishments include its use in the construction industry, in road construction, as an agricultural ameliorant, and use as a stabilising binding agent (Mäkelä and Höynälä 2000). The blast furnace slag produced at Raahe is a CE-certified product that conforms to the standard EN13242 and is used as a structural layer material and stabilising agent in earthworks and road construction, for liming purposes in agriculture, and as a raw material in the cement industry (Nikola and Mäkikyrö 2008).

In a subsequent process crude iron smelts are desulphurised by an injection of a calciferous reagent. A residual slag material called desulphurisation slag is formed, removed from the bulk smelt and generally air cooled. Desulphurisation slag has a high calcium oxide (CaO) content due to the reagent injection, with abundant silicon oxide (SiO_2) and elemental iron (Fe). The independent cooling process leads to an organised crystalline slag structure and affects the hydraulic properties and grindability of the slag. An average annual quantity of approximately 75 kt of desulphurisation slag can be produced at mills like Raahe.

Crude iron is refined into steel by oxidising and thus reducing crude iron’s carbon content through the use of converters, such as basic oxygen furnaces (BOF). The converter utilises additional feedstock such as recycled steel and various other raw materials, such as limestone, coke and ferrosilicon, with crude iron to maintain optimal process conditions and to enhance slag formation. The converter process produces a residual slag called converter steel slag. The slag is often independently air-cooled and has a high iron (Fe), calcium oxide (CaO) and silicon oxide (SiO_2) content, with the percentages of aluminium oxide (Al_2O_3) and magnesium oxide (MgO) being low. As a result of the cooling process, converter steel slag can establish a regular crystalline structure and according to Shi (2004), behaves as a weak Portland Cement clinker. A mill such as Raahe Steelworks can produce up to 130 kt of non-recycled converter steel slag annually. Converter steel slag from Raahe is commonly utilised as an asphalt filler in road construction (Rex 2003; Shi 2004).

After processing crude iron into steel, semi-finished products are generally produced within a steel mill. This processing is often managed through a process of continuous casting where the bulk steel smelt is directed from a ladle where the smelt begins to solidify as it is poured to the casting machine. At this process stage, steel ladle slag is generated. These slags are abundant in calcium oxides (CaO) and aluminium oxides (Al_2O_3). Silicon oxides (SiO_2) and magnesium oxides (MgO) are also present. A mill such as Raahe steelworks can produce up to 70 kt of steel ladle slag annually.

The total slag production in the EU in 2010 amounted to 23.6 Mt of blast furnace slags and 22.3 Mt of steel slags (EUROSLAG 2010). In 2010 the utilisation of blast furnace slags amounted to: 66% used in cement production or as a concrete additive, 23% used in road building and 11% stored or otherwise not utilised. Steel slags were utilised: 48% in road construction, 6% in cement production, 3% in hydraulic engineering, 3% as fertilisers, 13% landfilled, with other types of storage or onsite utilisation accounting for 27% of the total (EUROSLAG 2010). Steel slags are therefore still a focus for improved utilisation within the industry.

3.6 Residues as raw materials

The recycling and efficient utilisation of waste materials is among the new priorities in the sustainable development field (de Wolf et al. 2006). Such utilisations are therefore more eco-efficient by virtue of their energy recovery or the saving of virgin raw materials.

In Finland traditional process industries are known for their reliance on high volume raw materials and the generation of large solid residue streams (Pöykiö et al. 2005a). The relative stability of process conditions and the fact that operating conditions and the raw materials used in these processes do not change considerably, means that physical and chemical properties of residues and the homogeneous quality of individual residue streams promotes their potential for ready utilisation (Nurmesniemi et al. 2007). For suitable residues this therefore offers up possibilities to reduce raw materials and energy consumption from virgin materials acquisition and to avoid environmental impacts caused by the landfilling of such residuals. It has also been suggested by Nurmesniemi et al. (2007) that with more active management efforts, it might also be possible for residues to be modified to achieve desired qualities and further residue utilisation could be attained. Here residue in-process management and modification has been shown to be possible in particle size fractionation/sieving in the case of fly ashes in power plants for example. In this approach, multi-chamber electrostatic precipitators (ESP) are installed and fly ash particles having the biggest particle sizes accumulate in the first field, whilst the last field has more of the smaller particles. Metals concentrations are partitioned between different size fractions of ash such that according to Dahl et al. (2009) electrostatic precipitation can be an adequate method for the fractionation of fly ash to manipulate the quality of particular fractions for use as a fertiliser or for soil amendment purposes. A designed electrostatic fractionation approach is geared towards separating the fractions with high fine particle densities and hence high heavy metal concentration from the portion that is most suitable for practical applications such as re-use in residue-derived products.

The main utilisations currently undertaken and those under research and development for various pulp and paper process industry residues range from use as aggregates in concrete, soil amendment, cement production, brick production and concrete additives; for steel industry residues they range from use in blended cements, as soil amendments, as a solidification matrix for wastes, as road construction aggregates, for hydraulic engineering, as fertilisers, in masonry mortars and as construction products (Mäkelä 2012). Although the steel industry has been successful in improving utilisation rates especially for blast furnace slags, more options for steel slags are still needed (EUROSLAG 2010).

The direct application of industrial residues to soil is being investigated increasingly to facilitate de-acidification and amelioration of land and could become a future alternative option to chemical fertilisers. In the case of the ferrous metals and the pulp and paper industries, beneficial utilisation of unavoidable process residues could be managed through their combined use in applications such as soil amendments for example. The use of steel slags is an interesting area here in combination with other process industry residues according to Mäkelä (2012) and Mäkelä et al. (2011; 2012; 2012a; 2012b), as are the direct application of pulp and paper industry residues such as ashes, slaker grits and green liquor dregs according to Dahl et al. (2010), Manskinen et al. (2010; 2011, 2012), Nurmesniemi et al. (2010a; 2010b) and Watkins et al. (2010; 2011).

Despite the promising results regarding the use of individual residue fractions in soil amendment, integration of residues from different industry sectors into a distinctive product concept could provide additional benefits. This has been part of on-going investigations by Mäkelä et al. (2010; 2011; 2012a; 2012b), and by Mäkelä (2012) who reports on residue mixtures or formulations, physical handling and distribution through manufacture of suitably dimensioned mechanically easy to handle fertiliser pellets where pH shock effects from easily soluble salts could be attenuated by avoiding rapid dissolution (Mahmoudkhani et al. 2004) and immobilisation and control of alkaline metal release could be attained by use of suitable binders. Additionally, increasing the broader sustainability of manufacturing processes with respect to soil nutrient recycling back to forest ecosystems (Augusto et al. 2008) and avoiding the impacts of primary fertiliser production should not be forgotten. In addition to the use of fertilisation in agricultural environments, attempts to increase energy security and to reduce reliance on fossil fuels via increased biofuels usage (i.e. wood) (Mäkelä et al. 2012b; EC 2009b) can also have undesired effects on the acidification of forest soils (Dahl et al. 2009) and will increase the quantity of ash residues arising for management.

Use of residues as fertilisers and ameliorants in forestry and agriculture

In Finland soil amendments are regulated mainly by the Fertiliser Product Act (539/2006) (VNa 2006b) that recognises organic, inorganic, liming materials and soil improvers, amongst others, and specifies that a fertiliser may not contain harmful substances, products, or organisms that when used in accordance with its instructions may cause harm to human or animal health or safety or plant health or the environment. A subsequent Decree on Fertiliser Products 24/11 (Ministry of Agriculture and Forestry Finland 2011) deals with harmful substances, products and organisms in fertilisers in more detail and includes pseudo-total[29] concentration limit values for potentially detrimental trace elements (As, Hg, Cd, Cr, Cu, Pb, Ni, and Zn) and pathogens, and further stipulates different limits depending on intended application as intended either for use in agriculture or in forestry. Further requirements relating to inorganic by-product-based fertilisers require minimum concentrations of essential nutrients such as 2% NPK (nitrogen, phosphorus and potassium) and 8% for calcium, magnesium, sodium and sulphur. Additionally in the case of ash residues used in forest fertilisation the values 2% potassium and phosphorus and 6% calcium are stated.

The new Decree 24/11 also relaxed some metals limits e.g. As (40 mg/kg; d.w.), and Cd (25 mg/kg; d.w.) superseding previous limit values of As (30 mg/kg; d.w.) and Cd (17.5 mg/kg; d.w.). Current legal limit values for these metals are therefore higher than those previously which has meant that some additional residue streams such as pulp and paper industry green liquor dregs may now also be candidates for increased utilisation since recent studies have shown that, depending on the specific mill type, these types of residue can comply with the lower limit values; cf. Manskinen (2013). Although there is no difficulty in applying these regulations directly to simple single residue stream-based fertiliser products to aid residue recycling (e.g. to ashes or individual slags and other single by-product residue streams), the legislation only applies to six designated fertilizer types and does not apply to products formulated from multiple residues (i.e.

[29] *Pseudo-total* - the use of a less aggressive digestion method designed to indicate bioavailabilty which does not completely degrade sample matrix; i.e. does not include metals fraction that is not available to organisms and therefore not of interest from an ecological point of view.

ones designed out of multiple residue streams such as, for example, novel multi-residue-based amelioration pellets concepts/formulations) however. This is discussed further in Section 4.

Use of residues as construction materials

In Finland there are legislative requirements set out for the control and use industrial residues such as ash, blast furnace slag, concrete, used tyres, crushed glass, paving materials and ferrosulphate gypsum as earth construction agents (Mroueh and Wahlström 2002; Sorvai 2003). The materials most extensively utilised for these purposes have been blast-furnace slag, concrete debris from demolition work and power plant ashes. The current Finnish environmental legislation sets limit values for both the total and leachable concentrations of certain heavy metals, and for chloride, fluoride, sulphate and Dissolved Organic Carbon (DOC) and Total Organic Carbon (TOC), for residues such as coal, peat and biomass-derived ash or crushed concrete (VNa 2006a; Watkins et al. 2010). Construction in this respect relates to the use of such residues for levelling of earth works and enhancing their mechanical bearing capacity and durability, at a maximum application rate of 150 cm depth (VNa 2006a). Construction works may also be *covered* or *paved*, where covering refers to protecting the emplaced material with a mineral layer, the minimum thickness of which must be 10 cm to prevent the spread of waste, and paving here refers to protecting with asphalt with a maximum void of 5%, or with another material with a corresponding level of protection, in order to reduce the seepage of rainwater (VNa 2006a; Manskinen 2013). These limit values came into force in 2006 and are applied if the residues are used in the construction of roads, cycle paths, pavements, car parks and sportsfields that are at least 30 m from water supply or other groundwater protection zones (VNa 2006a). However, if coal, peat and biomass-derived ash are to be used then limit values for both the total and leachable concentrations of Polychlorinated Biphenyls (PCB) and Polycyclic Aromatic Hydrocarbons (PAH) and selected heavy metals are also applied by a subsequent Finnish Government Decree (403/2009) that amends Decree (561/2006) (VNA 2009). Additionally, limit values for extractable concentrations of dissolved organic carbon (DOC), selected heavy metals, fluoride, sulphate and chloride are also set in Decree 403/2009 (VNa 2009), and residues must not contain any other harmful substances in such a way that recovery might cause a danger or hazard to health or to the environment (VNa 2006a).

Application control is achieved via an exemption from the need to hold a waste management permit if the requirements of Decree (591/2006) are fulfilled, i.e. the residue user submits a notification to a regional environment centre as environmental permitting authority. The competent environmental permitting authority can also relax the maximum limit values for certain compounds (i.e. they can be up to 30% higher than those set in the legislation) on the basis of the local environmental conditions at the site where the residue is planned to be used (VNa 2009). There are currently no limits set in Finnish legislation other than for coal, peat and biomass derived ash or crushed concrete. Residue types falling outside these narrow categories are not able to be utilised easily on the basis of such an exemption therefore, and so their deposition always requires an environmental permit (Watkins et al. 2010).

3.7 The environmental aspects of residue-based products

3.7.1 Greenhouse gases

Energy intensive industries, with their large greenhouse gas (GHG) emission footprints from direct fossil fuel use or fossil fuel generated electricity consumption, are receiving more and more attention in connection with climate change since worldwide industrial CO_2 emissions contribute about one third of total emissions (IPCC 1996).

The cement industry in particular could give rise to between 5% (WBCSD CSI 2009) and 8% (Ehrenberg 2000) of all man-made CO_2 emissions, with the calcination process for clinker production being the third largest anthropogenic source of CO_2 behind fossil fuel combustion and deforestation (WCED 1987). As an example of one useful replacement, substituting a proportion of Ordinary Portland Cement (OPC) clinker with granulated blast furnace slag (GBFS) in cement manufacture itself, reduces the energy use requirement and CO_2 emissions (Ehrenberg 2000). Total embodied energy will therefore decrease as the OPC replacement ratio increases. Reduced energy usage thereby reduces direct fossil fuel emissions and additionally the direct calcination emissions (from the cement making process chemistry itself) are also avoided. It is therefore evident that the replacement of OPC with suitable process residues (such as steel slags that have a very low CO_2 footprint for instance) will reduce the total embodied energy consumption of a concrete product made from such blended cements since the emissions generated during iron ore smelting will already have been assigned to steel manufacture, with only the residue material handling and grinding energy needing to be considered.

Approaches to the issue of reducing CO_2 emissions from the manufacture of industrial products by encouraging the utilisation of raw materials and by-products that have a lower lifecycle CO_2 content (i.e. ones that require less carbon intensive energy during production, use and disposal) are therefore receiving more attention as one of the many options available for emission mitigation (Princiotta 2009). Since the manufacture of commercial chemical fertilisers and cements (for instance) rely heavily on resource intensive and environmentally detrimental processes, such as mineral extraction, calcination and fossil fuel combustion, supporting more research on the possibilities for development of both fertiliser and cement substitution products manufactured from readily available bulk industrial residues has the potential to significantly reduce environmental impacts compared to products based on virgin raw materials.

3.7.2 Recycling of inorganic nutrients

Although the application of chemical fertilisers can have the ability to boost short-term crop production, attempts to increase soil pH often result in a lack of numerous bio-essential nutrients and the organic material required for the long-term, healthy functioning of the soil, with primary and secondary nutrients N, P, K, S, Ca and Mg often being deficient in acidic soils (Bolan et al. 2003). In the forest sector in particular, the use of various forest residues such as stems, roots and branches is seen as an environmentally friendly means of producing energy, however the removal of large proportions of degradable biomass from forest ecosystems most likely effects the natural cation (Ca^{2+}, Mg^{2+}, K^+ and Na^+) cycle of plant production and decomposition. Consequently, increased cation removal from the soil can increase the concentration of competitive H^+ ions in soil pore water and hence generate long-term acidification of the soil (Dahl 2010). Consequently, many researchers have reported investigations regarding the recycling of industrial residues from the steel, pulp and paper industries by soil liming or soil amendment to address this (Augusto et al. 2008; Cabral et al. 2008; Dahl et al. 2010; Husgafvel et al. 2012; Manskinen et al. 2010; Manskinen 2013; Mäkelä 2012; Mäkelä et al. (2011; 2012a); Nurmesniemi et al. (2010a; 2010b); Pöykiö et al. 2005b; Pöykiö and Nurmesniemi 2008; Watkins et al. 2010; Zambrano et al. 2007). Industrial residue application/recycling to soil is therefore being increasingly investigated to facilitate the de-acidification of such soils and may increasingly become an alternative option to chemical fertilisers in future.

3.7.3 Metals availability

The case of metals and micronutrient Zn phytotoxicity is well established and was extensively researched during the 1970s and 1980s regarding anthropogenic soil contamination and soil conditioning through sewage sludge applications to land. Currently, as stated by the EC (Filgueiras et al. 2002), detrimental Zn accumulation in regional soils and surface waters is not expected based on risk assessment (the EC has concluded that existing legislation, concerning sludge management and control, provides an adequate framework to address and prevent future risks related to Zn accumulation.) Here, Council Directive 86/278/EEC - on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture[30] (EC 1986) sets limit values for the total concentration of metals in soils and acceptable loadings based on annual application rates for Zn metal (equivalents) (kg ha^{-1}) used in the agricultural application of sludge to land. Hence, provided residue-based ameliorant products can be produced with similar compliant leaching characteristics then metals concentrations will not restrict their use in agriculture and forestry. However, in the proximity of water catchment areas, further research regarding potential surface water and groundwater contamination would be required.

Further, Finnish national legislation on fertilisers also highlights issues with other metals e.g. such as Cr (Ministry of Agriculture and Forestry Finland 2010). The differences in mobility and toxicity between the trivalent and hexavalent valence states of Cr having been acknowledged such that the statutory limit value for the total concentration of Cr regarding the use of (e.g. converter steel slag as a single residue stream for agricultural liming purposes) was revised, with the total concentration limit value of Cr having been converted to a limit value for soluble Cr(VI), and set at the low level of 2 mg kg^{-1} (d.w.). The issue of there being no such directly comparable limit values for multi-residue-based concepts in the current Finnish fertiliser regulations is addressed in Section 4.

3.7.4 Residue characterisation and performance

Extraction studies are carried out in the assessment of worst-case environmental scenarios, in which the components of the sample become soluble and mobile (e.g. metals). In this respect sequential extraction procedures are increasingly applied to attain information on the mobility and bioavailability of trace elements (Mäkelä et al. 2011). The use of sequential extraction relies on the ability to provide detailed information of the origin, mode of occurrence, biological and physicochemical availability, mobilisation and transport of trace elements (Filgueiras et al. 2002). However, as opposed to sequential extraction, total concentration determinations are often widely used instead by regulatory authorities to set limits, and this total concentration approach as a single basis for environmental impact assessment is clearly insufficient and has been questioned by Mäkelä et al. (2011) and Zufiaurre et al. (1998). The validity of the usefulness of sequential extraction methods over total concentration approaches as a tool for chemical speciation is confirmed in such studies.

In other words, the total elemental concentrations often set as statutory limits controlling utilisation represent a source term only for the unrealistic environmental

[30] *Directive 86/278/EE* - the Directive was adopted over 20 years ago to encourage the application of sewage sludge in agriculture and to regulate its harmful effects. The EC is assessing whether the current Directive should be reviewed for the limit values for seven heavy metals because since its adoption, several Member States have enacted and implemented stricter limit values for heavy metals and set requirements for other contaminants.

scenario in which the entire mineral structure of the solid material is dissolved. In this respect the use of total concentrations, for example of metals, as limits to residue suitability during characterisation therefore provides relatively misleading information for assessing the possible bioavailability and mobility of metals. In order to estimate the bioavailability of metals and their potential toxicity, it is therefore necessary not only to determine the total concentrations but also the different forms or processes binding the heavy metals to the solid phase of the sample (Filgueiras et al. 2002). Lack of detailed analysis of the association of trace elements, coupled with overly emphasised considerations regarding technical and economic feasibility, can therefore lead to poor judgments in residue utilisation. The exclusive use of total concentration limit values in describing possible environmental impacts associated with residue utilisation can therefore be regarded as insufficient in describing the real mobilisation capacity and behaviour of trace elements in the environment (Mäkelä 2012).

3.8 Policy context

The current and emerging (EU and Finnish) policy and legal framework is a strong driver for progress towards sustainable responses in areas such as resource use and recycling.

Sustainability through sustainable development is a fundamental long-term goal of the EU which has integrated sustainability aspects into multiple policies and legal instruments. The EU Sustainable Development Strategy was adopted in 2001 (EC 2001a) and was renewed in 2006 (EC 2006d). Sustainable production and consumption is one of the key focuses of broad environmental policy and aims to play a vital role in helping to achieve this goal. In the EU this issue will therefore have increasing importance in future environmental policy papers. The broad strategy is aimed at promoting economically, socially and environmentally sustainable development, including the application of multiple instruments such as regulations, incentives and market-based instruments, in order to achieve this. Implicit in this approach is the need for comprehensive, integrated and cross-sectoral approaches (to policy-making) and for the application of the main principles of sustainable development. The renewed strategy claims that there is a need for policy-making based on better regulation and on the principle that sustainable development must be integrated into policy-making (EC 2006d).

In general, progress towards sustainable resource use and material efficiency are among the key prerequisites for sustainable development. The first concrete steps of this new policy approach that relate to waste in particular were taken in the Communication on Integrated Product Policy (COM(2003) 302 final) (EC 2003a; 2003b), in the Communication on new Waste Strategy (COM(2005) 666 final) (EC 2005a), the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan and the proposals on sustainable consumption and production in (COM(2008) 397 final) (EC 2008a) aimed at improving the environmental performance of products and increasing the demand for more sustainable goods and production technologies. The proposals also sought to encourage EU industry to take advantage of opportunities to innovate and were an integral part of its renewed Sustainable Development Strategy (EC 2006d) and review (EC 2009a) which reinforced the commitment to meet the challenges of sustainable development and build on initiatives and instruments at EU and international level such, as through the UN.

The modernisation of the EU legal framework to assist this encompasses the introduction of *life-cycle thinking* and strong emphasis on progress towards a European *recycling society*. New key ideas include, for instance, preventing waste generation and promoting recycling and waste recovery, and particularly avoiding landfilling (a case in which resources are lost and there might even be future environmental liability arising from the disposed of waste.) Furthermore, the aim is to improve resource efficiency and reduce the negative environmental impacts of the use of natural resources (e.g. lower greenhouse gas emissions and climate change impacts). In order to move in this direction industrial waste management requires new approaches based on the *waste hierarchy* under the Waste Framework Directive (WFD) (EC 2008c) and life-cycle thinking, as well as further clarification of the implications of *end-of waste* (EoW) legislation and criteria for product systems utilising residues and wastes. Other issues encompass, for instance, application of *best available techniques* (BAT) in environmental permitting (EC 2010b), waste recovery and utilisation procedures as well as the chemical safety of residue streams and residue-based products. EU instruments therefore claim to encourage a comprehensive approach to sustainability including consistency between various instruments such as the WFD and integrated industry related instruments.

In brief, it is evident that the EU places increasingly strong emphasis on sustainable industrial development through the application of numerous mutually supporting instruments. In this respect the EU has introduced a number of Environmental Action Programmes (EAPs), each spanning several years. In earlier EAPs the emphasis was on preventing problems rather than on rectifying them once they had arisen (on a precautionary principle) and included the objective of steering consumption and consumer behaviour in a more environment friendly direction. These sought to achieve greater sustainability, not just at the Community level but also in Member States, in trade and industry, and among ordinary people, by encouraging everyone to take a more active role in protecting the environment.

A major step forward occurred with the 6th Environmental Action Programme (EAP6) 2002 to 2012, which covered the four priority areas of climate change, nature and diversity, environment and health, and natural resources and waste; subtitled - *Our Future, Our Choice* (EC 2010b). This promoted full integration of environmental protection requirements into all Community policies and actions, and provided the environmental component of the Community's strategy for sustainable development. Seven thematic strategies that constitute the framework for action represent a modernisation of EU environment policy-making, taking a broader, strategic approach building on the existing EU legal/regulatory framework and on an integrated approach (the effects of decisions in one policy area that have consequences on the others). This latest EAP also focussed on increasing the role of *market-based instruments*, in particular the use of taxation at EU and national levels to help meet environment policy goals and encouraging a shift in the burden of taxation from labour towards protecting the environment; as well as improving the implementation and enforcement of existing legislation and quality of environmental regulation; actively encouraging the development and deployment of environmental technologies; and the promotion eco-efficient solutions. The refocusing of EU policy to achieve a more broadly integrated or more holistic approach is therefore clear. The sustainable utilisation of natural resources requires a new focus on optimal material cycles and material efficiency. Recycling and sustainable industrial development through improved process and product design are therefore key in this context.

3.8.1 Sustainable consumption and production

The EU's Thematic Strategy on Sustainable Use of Natural Resources COM(2005) 670 (EC 2005c) is a long-term strategy (25 years) that is part of EAP6 aimed at decoupling the environmental impacts of resource use from economic growth. Its aim is to integrate the assessment of the environmental impacts of using natural resources into policymaking in line with sustainable development. It is linked with the Commission's two other initiatives: Integrated Product Policy (IPP) (EC 2003a) and the Thematic Strategy on Prevention and Recycling of Waste (EC 2005a) (see Section 3.9.2). Importantly, the strategy proposes a wider application of life cycle approaches in current and future policy making. In particular the Thematic Strategy hoped to promote a comprehensive approach to waste prevention and recycling covering issues such as the utilisation of waste as a valuable resource to be recycled for further use in manufacturing industries.

The results of EC public consultation on 'Sustainable Consumption and Production' and 'Sustainable Industrial Policy', that were aimed at seeking actions the EU could undertake to meet the challenges involved, resulted in the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan (EC 2008a) that aims to integrate sustainability into industrial policy. The strategy covers actions with respect to innovation, better products, leaner and cleaner production and smarter consumption, as well as requirements for updating the general policy framework. The action plan builds on several existing EU policies related to products and resources, such as industrial policy, integrated product policy, the Sustainable Use of Natural Resources Strategy (EC 2005c), energy policy and other product legislation such as labelling schemes.

Developments at the EU level (EC 2003a; 2008a; 2008c; 2009c; 2010b; 2011d) and policies on raw materials, all now emphasise the importance of achieving a *recycling society* that seeks to avoid waste and uses waste as a resource (EC 2005a). This approach requires both a more sustainable use of natural resources and a higher level of *material efficiency* (MEf). EU guidelines for preparing National Waste Prevention Programmes (12th December 2013 deadline) mention the MEf concept as one of several alternative approaches to Waste Prevention (EC 2010c), for instance, preference of recycling and utilisation of waste and various residue materials over final disposal (the current main management option) (EC 2008c). The objective of achieving a recycling society in the EU will see the EC continue to monitor the implementation and enforcement of waste legislation at national level, including the requirements of the new Waste Framework Directive (EC 2008c) (see Section 3.9.2), and also seek to develop support for Member States in designing appropriate upstream strategies and policies.

To further consolidate its waste policies, the EC made further proposals in 2011 on setting out the concrete steps it will take in order to move closer towards an EU *resource-efficient recycling society* (EC 2011b). Further subsequent policy in the form of the Integrated Industrial Policy (IIP) also looks to enable the transition of EU industry to a low carbon and resource-efficient economy with a focus on the whole value and supply chain (i.e. a life-cycle perspective), from access to energy and raw materials, to the recycling of materials (EC 2010a). Key IIP focus areas include recycling and increased use of secondary raw materials. This approach also claims to advocate *life-cycle thinking* and hopes to promote good environmental performance with special emphasis on products. The concept of a recycling society implies reduced use of virgin materials and energy as well as enhanced closure of material cycles and lower emissions levels (EC 2005a; 2008c; Fischer and Davidsen 2010).

It is clear that such integrated EU approaches now place a strong emphasis on life-cycle thinking and continuous improvement of the environmental performance of products throughout their whole life-cycle (EC 2003b; 2009c). Emphasis is also placed on cooperation in the supply chain and on overall industrial modernisation with focus areas such as resource efficiency, utilisation of secondary raw materials, substitution of virgin raw materials, new *end-of-waste* (EoW) legislation and criteria, implementation of the *waste hierarchy* and increased recycling (EC 1996; 2005a; 2008a; 2008b; 2008c; 2010a; 2010c; 2011a; 2011c).

Finnish context

The challenge for industry in interpreting the idea of a recycling society is that this concept tends to focus on post-consumer waste (such as municipal waste and the end of life sectors). High volume primary residues from the process industries and residue-based by-products (as addressed in this work) are largely a marginal question there. For example, in the case of Finland, with its relatively large process industries in proportion to its economy, commercial and municipal waste quantities are very low (at only 2.8% of total wastes arising) compared to those from industrial sources at 12.9%, mines and quarries 49.7%, construction 24.6%, energy 1.4% and forestry, agriculture and fisheries at 2.8% (Statistics Finland 2012).

It is also important to note that in the case of Finland the renewable, recyclable and biodegradable products of the forest industry, based as they are on domestic natural resources, naturally forms part of its approach to sustainable and acceptable consumption patterns. The combined waste generation share of the forest products and metal industries is very large (76% of total industrial waste in Finland in 2006)[31] but there is little detailed information available on industrial waste management, since it is often arranged through disposal to on-site landfill or in some other industrial facility, and it may also involve waste processing before landfilling (MoE 2010).

The likely gains from industrial residue utilisation are therefore potentially greater in Finland than other EU countries due to the relatively large process industry character of its industrial base.

3.8.2 Life cycle thinking

The concept of *life cycle thinking* in general and specific *life cycle assessments* (LCA) covering the whole production and product chain can be major sustainability management tools. Adoption of a life cycle perspective to the assessment of industrial activities can lead to improved environmental performance of products and processes, and informed company level decision-making can be supported significantly by such sustainability management tools (Finnveden et al. 2009).

Within the context of recycling of process industry residues, other drivers for life cycle thinking also include the development of new markets for residue-based products, the potential for innovative and synergistic local applications, avoided waste management and landfill costs and also opportunities to credit primary industrial processes through avoided environmental burdens, by-product/process replacement and reduced waste generation. In view of this, life-cycle thinking is strongly recommended in implementing legal and voluntary environmental management approaches. Such total life-cycle approaches towards more sustainable consumption and production of products extend traditional pollution prevention thinking to include ecodesign and environmental impacts during the product use stage. This approach integrates drivers from areas such as eco-labelling, producer responsibility and product stewardship, corporate social responsibility reporting, finance market drivers, supply chain demands, the use of environmental management systems (EMS) and general stakeholder relations. The Ecodesign Directive (EC 2009c) in particular also claims to apply a life-cycle perspective with a focus on the main environmental aspects over the life-cycle of

[31] http://www.ymparisto.fi/default.asp?contentid=162446&lan=en#a3

products, particularly energy (improvement of energy efficiency) and resource use of products.

Life-Cycle Assessment - LCA

As the interest and public awareness of the impact of industrial activities on the environment increased towards the end of the 20th Century, the need for a system or tool to evaluate and compare various production options with respect to their environmental impact became evident (Dahl et al. 2008). One technique developed for this purpose is life-cycle assessment or analysis (LCA). In the past, environmental management studies and activities have focussed on specific sites such as on the impacts of new developments or on impacts arising from modifications to industrial processes in relation to point source emission standards. However, more recently, the heightened awareness of the importance of environmental protection, and the possible impacts associated with manufactured products (or services) and their consumption and use phases, has continued to increase the interest in the development of these methods to better comprehend and reduce impacts by using a different life-cycle thinking approach (Dahl et al. 2008).

The LCA approach studies the potential impacts arising from environmental aspects throughout a product's life-cycle *from cradle to grave*, in other words from raw material acquisition through production, use and disposal, using general categories of environmental impact such as resource use, human health, and ecological consequences. The scope, boundaries and level of detail of an LCA study will depend on the subject and intended use of the study. LCA involves calculating emissions to the environment resulting from the procurement and consumption of raw materials, energy generation, product manufacture, and (depending on the system boundary) the use, reuse and recycling or final disposal phases. Functional outputs in terms of emissions can be calculated per product unit of production or service, (i.e. per tonne), and each emission is given a value for use in a final impact assessment calculation step. LCA allows, at least in theory, a comparison of the environmental loadings and other environmental effects of different products and of the same product manufactured in different ways and it is now becoming considerably easier to make the appropriate choices and indeed to manage LCA analyses as a whole (Dahl et al. 2008).

Organisations can use LCA as a tool to seek ways of reducing the environmental impact of their products and processes. The usefulness of LCA in relation to this study includes:

- Comparing alternative systems (or sub systems) or evaluating trade-offs between system stages in relation to improvements;
- Assisting in decision-making in industry, e.g. for strategic planning (decision support at an organisational level), product or process design, or redesign;
- Assisting in decision-making in government planning, (e.g. resource and waste management policy) leading to regulatory instruments or guiding research and development funding;
- Supply chain management, focus on upstream suppliers;
- Marketing, (e.g. for an environmental claim or eco-labelling scheme or environmental product declaration), and
- Industrial ecology, linking process streams and seeking opportunities for inter- and intra-industry materials and energy interactions.

As only one of many environmental management techniques available (for example, risk assessment, environmental performance evaluation, site-related environmental auditing, and environmental impact assessment) LCA might not be the most suitable technique to be used in all cases. For example LCA typically does not address the economic or social aspects of a process or a product/service. The approach also includes optional subjective judgement elements on the relative importance of environmental impacts, so rival product and system comparisons are problematic. For example the application of differing impact methodologies that select impact categories and indicators, and characterisation models that generate common equivalence units that can be summed to give and overall impact category total. Normalisation, grouping, and weighting may also be done depending on the goal and scope of the LCA study. In normalization, results of the impact categories are usually compared with the total impacts in the specific geographical region in question. The sorting and possible ranking of the impact categories also introduces subjectivity, as does any weighting applied. In weighting, different impacts are given relative weightings so that they can then be summed to get a single number for the total environmental impact, although this is advised against in cases of comparative LCA studies intended to be used in comparative assertions intended to be disclosed to the public as advised by the ISO 14044 standard guidelines for LCA. A high degree of subjectivity can therefore result in comparative studies as a result of weighting. In general, an LCA study should be used as part of a much more comprehensive decision process or used to understand the broad or general trade-offs involved with system choices and alternatives. Comparing the results of different LCA studies is therefore only possible if the assumptions and context of each study are the same and it has been in the area of product manufacturers' relative environmental claims that issues of study comparability have been problematic for the technique. These assumptions in LCA studies should therefore be explicitly stated for reasons of transparency.

In this sense LCA is perhaps most useful in product planning, the stage at which alternative products are compared in terms of their likely environmental effects. However, the choices made reflect the weaknesses of LCA since despite the values allocated to different emissions, assessments based on environmental impact are in practice only approximate. The effects of the different emissions also vary according to location, for example the same level of the same emission can have different effects depending on the nature and sensitivity of the receiving media, e.g. in the case of treated effluent discharges to water the type and quality of the receiving watercourse or lake (Dahl et al. 2008). However, despite these drawbacks the EC has concluded [in its communication on Integrated Product Policy (COM(2003) 302) (EC 2003a)] that LCA thinking provides the best framework for assessing the potential environmental impacts of products currently available and so it is set to remain an important tool in future (see Section 3.8.1).

Most commercially available LCA software models are now able to import and export harmonised standard format data sets and LCA methodologies assisted by the EC who are facilitating the European Platform on Life Cycle Assessment (EC 2013) in order to facilitate communication and exchange of life-cycle data and launch a co-ordination initiative involving both on-going data collection efforts in the EU and existing harmonisation initiatives. The platform provides quality-assured, life-cycle-based information on core products and services as well as consensus methodologies to assist in integrating life-cycle thinking into product development and policy making.

The LCA software used in this work [GaBi software (PE International 2006)] has been developed in accordance with the requirements of environmental management standards concerning the principles and framework for an LCA (ISO 14040) and the requirements and guidelines for LCA (ISO 14044), and it is compatible with the International Reference Life Cycle Data System (EC 2010d) and also utilises a common impact assessment method (PE International 2006).

Exergy approach

The idea that economically and ecologically justifiable level of recycling to further use could also be assisted by using *entropy production* as a measure for the associated costs; cf. Gössling (2001), means that in addition to LCA the use of concepts such as *exergy* are also potentially useful. The concept of exergy provides a straightforward and scientific base for the analysis of processes with a focus on the assessment of resource use efficiency. Exergy analysis calculates the exergy efficiency of the material and energy flows in production processes in relation to the produced end-products and is applied in a limited sense as an adjunct to LCA in one study included in this work.

LCA and EU Integrated Product Policy

Integrated Product Policy (IPP) (COM(2003) 302) (EC 2003a) aims at reducing the environmental impact caused by products, encompassing multiple actions to promote continuous improvement of the environmental performance of products throughout their whole life-cycle encompassing, for instance, resource, energy and carbon efficiency (EC 2003b). Finnish forest industries, as ones based on predominantly renewable raw materials, should benefit from IPP in the EU. The EU strategy of IPP is aimed at stimulating greener products and is therefore an integral part of the Action Plan on Sustainable Consumption and Production (EC 2008a). The stated aim of IPP is not an attempt to reduce consumption, but rather, to seek to reduce the environmental impact of increased consumption and outlines a strategy for reducing the environmental impact caused by products via actions to stimulate continuous improvement in the environmental performance of products throughout their life-cycle.

Products with the greatest potential for environmental improvement will first be targeted by working with industry, business and consumers to 'green' those products. Previous environmental product-related policies have tended to focus on large point sources of pollution, such as industrial emissions and waste management issues, rather than the products themselves and how they contribute to environmental degradation at other points in their life-cycles (especially the use phase). In this sense the IPP approach to environmental protection is a new one, one that looks at all the stages of a product's life cycle, from cradle to grave, and seeks to reduce the overall environmental damage it causes at different stages. The IPP approach requires full stakeholder involvement encompassing all actors during the whole life cycle of products, namely producers, consumers and the waste management industry. In this way appropriate action can be taken at the appropriate problem stages in the product life-cycle. This approach also avoids just shunting the environmental impacts from one phase of the life-cycle to another. Instead, the goal is that the approach should reduce the overall environmental impact.

The IPP approach claims to aim at improving both the existing instruments (more focus on products) and the environmental performance of products that have the best potential for environmental improvement (EC 2003b). Implementation of IPP is via improving the tools that already exist to make them more product-focussed, including environmental management systems [such as the EU Eco-Management and Audit Scheme (EMAS), (EC 2009d)], eco-design and environmental labelling [such as energy and eco-labels (EC 2009c)], the provision of life-cycle information (see Section 3.8.2), and by taking action to improve the environmental performance of products that have the greatest potential for environmental improvement. In this respect the first steps took place in 2006 (JRC 2006), that looked at impacts of consumption of final consumer items. However, there is as yet no specific IPP type focus on process industry's *primary* *products*, in other words, on products that are raw materials inputs to other manufacturers of consumer products.

3.9 Drivers and barriers - EU waste policy and law

The traditional way to control industrial activity has been command and control via legislation. There are number of environmental regulations that prohibit the use of certain substances or set emission limits, for example environmental permits that set point source emission limits, requirements of the certain technical standards to be used such as *Best Available Techniques* (BAT) under integrated pollution prevention and control (IPPC), and industrial emissions control (IED) legislation (EC 1996; 2010b), or producer responsibility in waste legislation for example. The use of restrictions and permissions providing guidance for land use can also be considered part of the legal control mechanism. This part of the legal system tends to create a rather simple system, where the obligations must be met in order to start or continue operation. In this sense environmental regulations are generally regarded as the main drivers for environmental protection-focussed efforts, investments in end-of-pipe solutions by industry for example, at least at the beginning when environmental protection activities are found to be necessary due to gross environmental insults. Indeed, in industrialised countries, investment in environmental protection in connection with all productive investments in industrial processes and plants is generally obligatory and routine, and new regulations may also require investment in pollution abatement equipment for existing plants (Salomaa and Watkins 2009).

However Moon (2007) emphasised the essential role of companies in promoting and working for the progress of sustainable development through environmentally sustainable economic activity as the basic provision and key to adapting to broader agendas, for instance the concept of corporate social responsibility (CSR). By environmentally responsible investments and production methods industry can contribute to maintaining a safe living environment and more ecologically sustainable conditions. However Salomaa and Watkins (2009) further point out that although the motivation for environmental protection investment in general may in principle be to protect the environment for obligatory or voluntary reasons, ultimately the investment decision is based on economic criteria. It is sometimes not possible to show returns over the short term for environmental investment, but, if required by regulations, the investment may still be absolutely necessary for the continuity of production (i.e. to ensure continuing to hold an environmental permit) or to avoid negative legal consequences. Thus, environmental regulations can be seen to induce environmentally related technological change in industry; cf. Altman (2001) and Porter and van der Linde (1995). Although the level of environmental protection in the Finnish forest industry can be regarded as quite high, there is increasing pressure for further utilisation of industrial residues and wastes (Salomaa and Watkins, 2009). According to Pöykiö et al. (2006) increasing costs of landfill disposal, difficulties in acquiring new sites for disposal and development of environmental management systems are all driving forces in minimising the amount of solid wastes arising for disposal.

If we consider the historical development of regulatory approaches then environmental legislation includes both these traditional categories of environmental protection, pollution control, environmental assessment and waste management, but also new categories such as emissions trading and environmental aspect based taxes. Economic and voluntary market-based instruments, like taxes, environmental management systems and reporting, competition for market shares and prices of raw materials might be effective drivers to heighten responsibility of the industrial actor to make decisions to adopt more eco-efficient approaches. Informative instruments, like education, communication, ecolabels, environmental footprints and other similar material, are aimed at increasing knowledge of environmental issues and understanding the consequences of industrial activities. Other drivers, such as CSR, stakeholder pressure, non-governmental organisations and general public pressure, will also affect the final decision. Pressures such as these have led companies to increasingly use ISO14001 standard-based environmental management systems (EMS) to manage their impacts [such as EMAS in the EU for example (EC 2009d)]. Reporting practices are also changing in more complex directions, such as towards CSR in relation to activities impacting on consumers, employees, local communities and other stakeholders, from earlier approaches focussing solely on environmental performance. However, for a company to act, sufficient incentives are still needed, often in the form of economic benefits (Porter 1995).

A major issue that determines the management route for post-production materials concerns the way in which they fall to be treated institutionally as falling into the product, by-product or production residue, or waste flow categories. How these categories, and the legal aspects controlling their management are determined, the impacts on the options available for their environmentally beneficial management downstream, and how these arrangements are currently set out is the subject of this section. The way in which residues from primary production generally fall into the control of either product or waste legislation is shown in **Figure 17**.

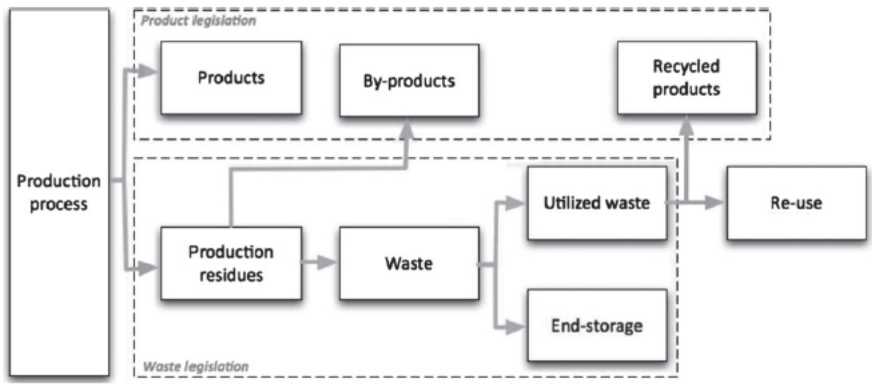

Figure 17 *Operation and interconnection of product and waste legislation - Paper* II

3.9.1 Waste prevention and reduction practices

Different types of waste prevention and reduction practices can be identified: (1) Reducing generation by process re-design, input substitution or plant improvement; (2) Finding new ways for reuse and recycling of by-products, for instance by developing large-scale networks of efficiency improvement through development of large industrial ecosystems; (3) Implementation of new innovations; and (4) Increasing waste storage capacity (Salmi et al. 2011). Practices 1 to 3 can be correlated with the EU prevention policies to reduce, re-use and recycle wastes which were discussed in Section 3.8.

The first approach comprises waste management procedures that tend to reduce the production of such production residues that can be categorised as waste. The main environmental effort can be classified as developing the *end of the production process* (Moors et al. 2005). It aims to reduce environmentally problematic emissions by improving emission capture technologies, as well as aiming to improve the utilisation of by-products by processing the residues. It is possible to reduce or eliminate the production of wastes to some extent by changing the input materials to the production process in some circumstances. This approach fits well with the general industrial logic of constantly assessing the use of energy and other resources, the raw material inputs and the operational designs to seek efficiencies. However, there are great differences between production sites around the world. Europe, with relatively strict environmental legislation, has obtained remarkable results by adopting this strategy (Salomaa and Watkins 2009).

The second approach of transformation of the quality of the already produced residues in order to find new ways to reuse them, includes rather simple technical solutions in the target industries, such as slag quenching and screening, and more complicated procedures like fine milling and mixing of residues (Mäkelä 2012; Wierink et al. 2010). Much work has also been put into finding markets for these types of products. However, this waste management strategy is becoming more difficult as the legislation and its interpretation is becoming more strict (Salmi et al. 2011). This particular approach is one focus of this work.

The third level of waste management is that of developing new and modifying existing production processes via 'green engineering'. These technologies need years to mature and become industry standards or accepted as best available techniques (BAT) and must of course present a marked economic improvement if a company is to make the required investment on an operating plant.

The final approach (of storage or landfilling) is a straightforward waste management procedure, however availability of suitable storage/landfill capacity is still the single most important aspect here and one that is under pressure due to stricter environmental legislation and the consequent higher costs of disposal. The environmental permitting of new landfill sites is now more strictly regulated making the access to new deposition sites more difficult. This is most critical for the high volume wastes from process industries that have not yet found any suitable utilisations. This level of waste management does not pose major engineering challenges, rather the challenges relate to securing space and permissions to continue this simple and robust waste management procedure and the long-term environmental risks associated with such landfilling practices.

Resource efficiency and best available techniques (BAT)

A much more complex system of drivers and barriers can be seen when dealing with improving resource efficiency (which includes energy resources) and more specifically that of material efficiency (MEf). Here, environmental legislation is also designed to be one of the major drivers for improvement. The use of approaches preventing waste and encouraging the re-use and recycling of materials is therefore at the forefront of this policy.

The EU recently placed even more emphasis on material efficiency with the Raw Materials Initiative which hopes to encourage sustainable supply of raw materials and to reduce primary raw materials consumption (EC 2008b). This initiative recognises the significant role of secondary raw materials and notes the increasing use of, and demand for, recycled scrap. Key measures mentioned are the creation of enabling conditions for increased recycling and reuse of materials with a focus on the development of the legal framework, [e.g. recycling and when waste ceases to be waste or so called *end-of-waste* criteria (EoW*)* – See Section 3.9.2] and on both the use of secondary raw materials and substitution of raw materials (EC 2008b). The Resource Efficiency Flagship Initiative (EC 2011a) – *A vision of where Europe should be in 2050* – also claims that resource efficiency refers to sustainable use of limited resources and hopes to initiate a change towards more sustainable resource management. This involves the development of new products, reduction of inputs, low-carbon technologies to reduce emissions, minimisation of waste and more sustainable production processes with the essential role of concepts such as extended producer responsibility and resource efficiency. The core elements of the EU approach to resource efficiency encompass, for instance, increased recycling to (1) reduce demand for and pressure on primary raw materials, (2) support re-use of valuable materials instead of disposal as waste, and (3) reduce energy consumption and greenhouse gas emissions (EC 2011a).

Material efficiency

The concept of material efficiency (MEf) covers a much wider area than waste prevention (WPr) or utilisation as it focuses on the whole life cycle of specific materials and is a major international and EU theme. MEf can be improved by residue utilisation covering for example the creation of new by-products. According to Lilja (2008), MEf related agreements (similar to energy efficiency agreements[32] based on industry sectors) could also promote WPr more effectively than steering through norms and permits. The use of such MEf agreements could create long-term commitment and contribute to increased flexibility and stronger industry-regulatory authority partnerships. This is expanded upon in more depth in Section 4.

Industrial emissions and BAT

The new Directive 2010/75/EU (EC 2010b) on industrial emissions (IED) [an update to existing integrated pollution prevention and control legislation (IPPC) (EC 1996)] aims at reducing industrial emissions with special emphasis on an integrated approach that includes emissions, waste management, accident prevention and energy efficiency, and on the application of BAT and related technical guidance (EC 2010a). In this context, the integrated approach refers to addressing the environmental performance of a specific industrial plant or installation *as a whole* in environmental permits. Thus, environmental permitting may now therefore be able to include focus on the use of raw materials in the form of MEf (Lilja et al. 2012). The general principles[33] that govern the basic obligations of the operator of installations comprise those of waste prevention and recycling in accordance with the Waste Framework Directive (WFD) (EC 2008c) and energy efficiency.

The term BAT, refers to both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned. In practice this means the most up-to-date stages of development/state-of-the-art of processes and their methods of operation, the technologies on which they operate, taking into account the practical suitability and cost of a particular technique for preventing, or where that is not practicable, minimising emissions to the environment as a whole and achieving a high general level of environmental protection. Specific BAT Reference documents (BREFs) have been prepared for the paper and pulp industry (JRC EIPPCB 2001) and iron and steel industry (JRC EIPPCB 2012), amongst others.

The choice of BAT is often the eco-efficient choice; waste-to-energy treatment is considered BAT for example, since the energy content of the wastes are utilised in the form of heat and through electricity generation, and this therefore saves virgin resources (EC 1996). In practice, the integrated approach means that the environmental performance of an industrial plant must be addressed *holistically* (i.e. as a whole in

[32] http://www.energiatehokkuussopimukset.fi/en/
[33] WFD, Article 11, OJ L 334, 17.12.2010, p. 27.

environmental permits). This could now therefore imply more focus on the use of raw materials, in other words specifically on MEf.

3.9.2 Waste Framework Directive

The EU's Sixth Community Environment Action Programme (EAP6) called for a revision of the legislation on waste[34]. In line with this, the new Waste Framework Directive (WFD) (2008/98/EC) (EC 2008c) has a policy aim of reducing the use of resources. In reality this is possible through both waste prevention and also via efficient re-use and recycling of material[35]. The recovery of waste is being encouraged therefore in order to reduce the use of natural resources and promote sustainability. The WFD therefore covers measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use.

The WFD aims at encouraging sustainable use of residues by attempting to clarify the *waste status* of certain materials and by delimiting its scope of application only to materials and substances defined as waste[36]. In order to attempt to streamline the situation new tools have been introduced aimed at helping industry to more efficiently use side-products and other valuable waste resources. A term has now been developed between those of a *waste* and a *non-waste* (i.e. product) namely a *by-product* and there is now the possibility to set criteria to define so called *end-of-waste* (EoW). This introduces the possibility that certain waste streams that have undergone a recovery operation can cease to be waste if they fulfil certain EoW *criteria*. The EoW criteria are the requirements that have to be fulfilled by a material derived from waste, and which ensure that the quality of the material is such that its use is not detrimental to human health or the environment. The EoW criteria are therefore an important key development for the development of environmentally beneficial residue management options.

Waste hierarchy

The fundamental element of the WFD is the *waste hierarchy*[37] which lays down a priority order of what constitutes the best overall environmental option in waste legislation and policy. The hierarchy runs from: 1) waste prevention, 2) preparing for re-use, 3) recycling, 4) other recovery (such as energy recovery), to the least preferred option of 5) disposal (landfill predominantly). In practice, the waste hierarchy steers the different waste prevention, recovery and disposal options in line with the obligations of the directive which specifies the prerequisites for using waste as a resource and substituting natural resources by residual materials. However, departing from the hierarchy may be necessary for specific waste streams if justified for reasons of, *inter alia*, technical feasibility, economic viability and environmental protection[38].

The definition of waste

According to the WFD[39] certain specified waste shall cease to be waste when it has undergone a recovery (includes recycling) operation and complies with specific criteria to be developed in line with certain legal conditions. In this way the aim is to further

34 EAP6, Article 8(2).
35 WFD, Preamble 6.
36 *Ibid.*, Article 3.
37 *Ibid.*, Article 4.
38 *Ibid.*, Scene 31.
39 *Ibid.*, Articles 6 (1) and (2).

encourage recycling in the EU by creating legal certainty and a level playing field as well as removing unnecessary administrative burdens that influence decisions made on virgin versus secondary material choices. The WFD's recent introduction of the EoW criteria route recognises the increasing importance of waste recovery where provided the statutory conditions are complied with and there has been sufficient recovery, material can cease to be regarded as waste. This also confirms the commitment to developing EoW criteria for materials such as construction and demolition waste, some ashes and slags, scrap metals, aggregates, tyres, textiles, compost, waste paper and glass.

As it is not always simple to interpret whether the definition is met or not, additional information is required. Commission Decision 2000/532/EC (EC 2000), established a harmonised, non-exhaustive list of wastes aimed at providing common terminology by a reference nomenclature even though it does not have to be adopted word-for-word in national legislation. It applies to all wastes, irrespective of whether they are eventually disposed of or recovered. However, it is to be noted that the inclusion of a material on the list does not mean that such material would always be regarded as waste, since in a legal sense waste is defined by the actions or intention of the holder, not so much by the nature of the material, although the material properties may suggest that waste status is probable. Some researchers are of the opinion that the definition originates from practical problem solving of waste management and therefore lacks scientific accuracy (Pongrácz 2002). European Court of Justice (ECJ) case law has created a test that can be applied to resolve whether something is waste or not, in that in addition to the holder's intentions, the intentions of other parties, especially of the following recipient(s) of the material can also be important.

Significantly, the definition of waste has been clarified in the WFD through specific articles that formally introduce the concepts of *by-products* and *end-of-waste* status. The introduction of a definition of by-products in Article 5(1) formally recognises the circumstances under which materials may fall outside the definition of waste. This change is intended to reflect the reality that many by-products are reused before entering the waste stream. Here, a substance or object, resulting from a production process (the primary aim of which is not the production of that item) may be regarded as not being waste and as being a by-product instead, but only if the following conditions are met:

- if further use of the substance is certain;
- the substance can be used directly without further processing other than normal industrial practice;
- the substance is produced as an integral part of a production process; and
- the further use is lawful, i.e. it meets all relevant product, environmental and health standards for the specific use and will not lead to overall adverse environmental health impacts.

The WFD also contains revisions to the concepts of *recovery* and *recycling*. Recycling is now separately defined for the first time, and whilst the list of recovery operations in Annex II has remained the same, this is now stated to be a non-exhaustive list, potentially widening its scope. It is therefore possible that the use of such EoW criteria and the newly introduced definition of *by-product* will reduce the need for case-by-case evaluation by some degree. However, these new EoW criteria do not apply in cases where the potential product consists of a combination of several residues.

Waste or by-product?

In theory it is clear what is or is not waste, since the definition of waste is set down in law in the WFD, according to which waste means '*any substance or object which the* *holder discards or intends or is required to discard.*' The Waste List (Commission Decision 2000/532/EC) indicates what waste and hazardous waste are; however putting the definition of waste into practice causes difficulties both for the competent environmental authorities and businesses. These difficulties may appear as legal uncertainty, administrative costs, or internal market disturbance (EC 2005a). The ECJ has interpreted the waste definition in its various decisions and some guidelines are now also included in the new WFD which are based on guidance adopted into a Commission communication on waste and by-products to assist Member States to distinguish between 'by-products' and 'wastes' (EC 2007) (**Figure 18**).

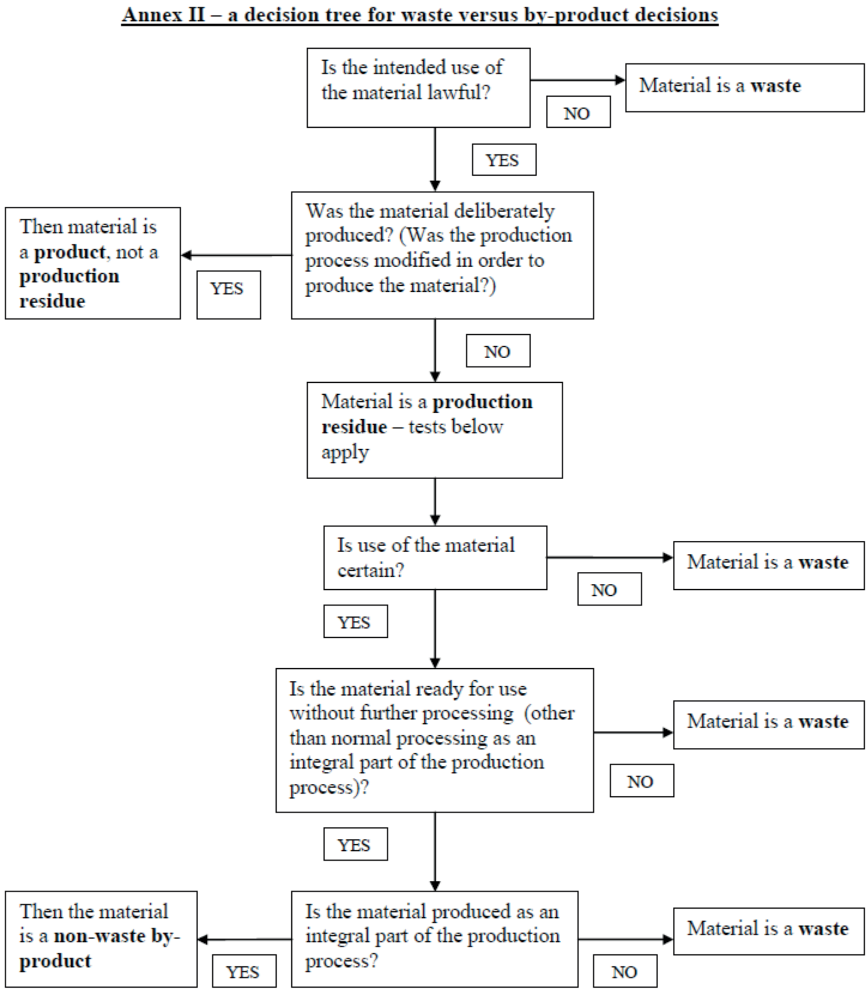

Figure 18 *A decision tree for waste versus by-product decisions (EC 2007)*

The ECJ has stressed the following themes in its decisions. Firstly, that the definition of waste must be interpreted widely, since a high level of environmental protection is the leading objective of EC environmental policy. Secondly taking into account the variety of materials and processes which are involved in industrial practices, then the decision as to whether a material is waste or not must therefore be taken by the competent authority on a case-by-case basis by focussing on the factual circumstances. Thirdly, that even if a material otherwise satisfies the criteria created by ECJ case law and would therefore not be considered waste, factual circumstances could change this presumption. If a material is, in practice, discarded, it must clearly be considered and treated as waste. The importance of the notion of 'discarding' is thus clear.

Legal definition of waste and implications of waste label

The ECJ has been called upon to resolve many disputes, by interpreting the meaning of waste because of ambiguities contained in EC waste legislation and has developed a number of key criteria for assisting in the determination of the existence of waste in practice and has confirmed the very broad coverage/reach of the definition of waste. As the definition of waste is part of a directive, each Member State is therefore responsible for implementing it correctly through its own national legislation and this has caused the ECJ to be kept busy in this respect.

The major implication arising from these ECJ judgements is that once a material is considered to be waste it is then subject not only to the requirements and controls contained in the basic framework legislation of the Community pertaining to waste, but also a number of other specific EC legislative instruments addressing particular treatment operations and waste streams. The problem that stems from this is that so much may follow in terms of regulation from the classification of a substance as waste and it is for this reason that the national courts and the ECJ have needed to respond to cases from industry eager to avoid such labelling, where legally possible and environmentally acceptable. This issue appears to be a recurrent definitional struggle between permit applicants, environmental administration, administrative courts and citizens (Salmi et al. 2011).

End-of-waste criteria introduced

The idea of determination of *end-of-waste* (EoW) status makes it possible to develop criteria for specific waste streams that ensure environmental soundness of recycled materials. Criteria such as these could reduce administrative burden for operators[40], by clarifying when a waste ceases to be a waste the idea is that this should introduce regulatory relief for recycled products or materials that represent a low risk for the environment[41]. The WFD formulates the need for EoW criteria in the following way: '*In order to clarify certain aspects of the definition of waste, it is necessary to specify when certain wastes are to be deemed to cease to be a waste and to become a secondary material or substance, on a category by category basis. The provision of a mechanism whereby reclassification is subject to criteria that provide a high level of environmental protection should provide an environmental and economic benefit*.'[42]

The EoW criteria are all the requirements that have to be fulfilled by a material derived from waste, and which ensure that the quality of the material is such that that material will not be discarded and its use is not detrimental for human health and the environment. The concept of EoW criteria implies that the waste material has reached a stage of processing whereby it has an intrinsic value, so it is unlikely to be discarded (the very definition of waste) and has been processed to a point at which its use does not represent a risk to the environment. The purpose of defining EoW criteria is to facilitate and promote recycling, whilst ensuring a high level of environmental protection, reducing the consumption of natural resources and the amount of waste sent for disposal. Currently, the recycling of certain wastes is sometimes hampered by several

[40] *Ibid.*, p. 6.
[41] *Ibid.*, p. 9.
[42] *Ibid.*, p. 14.

factors that could be overcome by determining when a waste ceases to be a waste and becomes a secondary product (JRC 2009).

Conditions for use of the EoW criteria

The WFD sets conditions for use of such EoW criteria whereby the residue stream at hand must pass a four step test:

- the substance or object is commonly used for specific purposes;
- a market or demand exists for such a substance or object;
- the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- the use of the substance or object will not lead to overall adverse environmental or human health impacts.

Such EoW criteria should be set for specific materials by the Commission and a mandate to set such criteria was introduced to provide a high level of environmental protection and environmental and economic benefit. Compliance with the first two conditions ensures that the material or substance is more likely to be put to a useful purpose and less likely to be discarded. These two conditions prevent the definition of EoW criteria for materials for which demand and market are not yet developed (a 'chicken and egg' situation for novel residue-based products). The third condition requires that a substance or object can only cease to be waste if it is fit for lawful use. Once it ceases to be waste, it would be covered by the legislation applicable to products; therefore EoW would only apply if the use of the material is lawful. The fourth condition means that the use of the materials or object does not merit the application of waste legislation. A comparison between the environmental impact of using the substance or material under waste legislation and its use under non-waste product legislation should be done to assess the overall impact of the EoW criteria.

However, the criteria are applicable only to certain waste streams specified in a separate procedure[43], and cannot be applied directly to potential products consisting of a combination of several residues for example. In this respect the waste-related regulatory framework does not explicitly address the legal challenges imposed by potential symbiosis products either. This issue in relation to industrial residue case studies is explored at length in Section 4.

Landfilling and classification of wastes

In the EU, if a residue falls to be treated as waste then it needs to be further classified in order to be correctly handled and managed at the correct type of waste management facility. In this respect the classification of residues for landfill disposal has been set out in the Landfill Directive 1999/31/EC which classifies all waste into one of three classes: either hazardous waste, non-hazardous waste, or inert waste (EC 1999). The assessment of waste classification needs to be performed before decisions are made on waste disposal to landfill to determine which landfill facility type can accept the waste.

If process residues need to be disposed of in non-hazardous waste landfills, the concentrations of harmful compounds must be low and these components must be tightly bound to the matrix (i.e. have low leaching characteristics). Therefore, before industrial residues can be utilised or disposed of to landfill, their chemical as well as extraction (leaching) characteristics must be known. During transport, disposal, and

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[43] *Ibid.*, Articles 6.2 and 6.4.

storage, residues may be subjected to the leaching effects of rain, and other substances, (e.g. chloride, sulphate, and organic matter), which may form complexes with heavy metals. The behaviour of materials under different environmental conditions is therefore very important to determine beforehand.

Possibility to landfill

In the EU's waste hierarchy, landfilling is seen as the least favourable option as it means that the resources and energy are lost and possible environmental liabilities generated[44]. Some Member States have used exemptions by excluding certain wastes to landfills from some provisions of the directive. Regarding waste acceptance criteria, some Member States have now defined criteria and procedures for wastes acceptable in landfills, implementing Decision 2003/33/EC (EC 2003c) establishing criteria and procedures for the acceptance of waste[45].

Recovery actions further defined - Recovery, re-use and recycling

In the past the meaning of these terms had always been problematic with their usage often having been interchangeable and not helping elucidate matters in the area of resource utilisation. This situation has been clarified somewhat with the WFD.

The basis for the definition of *recovery* is now defined as the substitution of resources[46]. The key idea here is to differentiate between *disposal* and *recovery* by setting of efficiency criteria where appropriate[47]. The definition now ensures a clear distinction between disposal and recovery based on a genuine difference in environmental impact, and more specifically on whether or not the operation leads to the substitution of natural resources in the economy.

The definition of *re-use* is now also defined as any recovery operation by which products or components that have become waste are used again for the same purpose for which they were conceived[48]. Re-use therefore differs from recycling in that the future (following) use should be the same as the former use, whereas in recycling the future use could be something totally different. In a way this reflects some qualitative aspects as it can be understood that re-use would in general entail the same or at most slightly decreased qualities from the raw material and/or final product. This implies that compared to other recovery options re-use would in most cases mean high(er) material efficiency. A further clarification in the case of *recycling* has also been added[49], according to which recycling means the *recovery* of waste into products, materials or substances whether for the original or other purposes. Here recycling can be understood as a framework definition that includes re-use as one way of recycling whilst also the original purpose of use is included. Recycling can be complete, meaning the whole of a waste is used, or partial if only some components of the waste are utilised. Partial use is of course of lesser material efficiency than complete use.

3.9.3 REACH Regulation

A substance or object can only cease to be waste if it is fit for lawful use (JRC 2009). When waste ceases to be waste, and instead is used as a product raw material the

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44 (EC 2005a), p. 4.
45 (EC 2006a), p. 9.
46 (EC 2005b), p. 10.
47 *Ibid.*, p. 10.
48 *Ibid.*, p. 17.
49 *Ibid.*, p. 10.

requirements set by REACH [Regulation (EC) No 1907/2006 (EC 2006c) concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals] may become applicable, unless covered by an exemption[50].

The framework of REACH forms the core of the new EU chemicals policy and regulatory system for chemicals. The main aim of REACH is to ensure a high level of protection of human health and the environment in accordance with sustainable development. The key implications of REACH for various companies are the registration requirement with the new EU Chemicals Agency (ECHA) for producers and importers of chemicals including the evaluation of related registration documents and substances. The authorisation procedures involve the assessment of risk management measures or of overall economic and social benefits when there are no alternative substances or technologies available. Additionally, companies have to maintain inventories of substances and their uses, including exemptions, and have a clear understanding of the origin of each substance as well as the determination of specific obligations concerning each substance from the perspective of their status as a manufacturer, importer or a downstream user.

Neither does EU waste law now exclude the possibility that even hazardous waste may cease to be waste within the meaning of the WFD (after a recovery operation for instance) and if it ceases to be waste, it therefore comes within the scope of REACH[51]. This would mean that the recycling of certain wastes would not be impeded by the presence of hazardous substances in waste. Hazardous waste may therefore be returned as secondary raw materials, with REACH playing an important role in this respect. This may be good news for sustainable materials management provided that adequate safeguards ensure the correct management of these residues in suitable utilisations and the appropriate assessment of associated environmental and health risks.

3.9.4 Finnish waste policy and legislative context

Finnish waste legislation covers all wastes and is largely based on EU legislation, but in some cases includes stricter standards and limits than those applied in the EU as a whole. Finland also has legislation on some issues related to wastes that have not yet been covered by EU legislation, with additional laws for waste treatment and recovery, specific waste types, products and activities, the storage and collection of waste for example.

The new Finnish Waste Act (646/2011), that implements the Waste Framework Directive (2008/98/EC) (WFD), includes the definition of EoW criteria as laid out in the WFD encompassing requirements concerning recovery/utilisation procedures, purpose of use, existence of market/demand, technical standards and health and environmental hazards or harm. This new legislation has multiple implications for residue management and symbiosis opportunities in a similar way to that of the overarching framework of the EU WFD. Particularly interesting areas include a strong promotion of recycling and increased use of recycled materials, the sustainable use of natural resources and the continuous improvement of waste management practices which are all duly re-highlighted within waste-related policy and legal instruments of Finland.

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[50] REACH - See ECHA (2012), REACH art. 2(2) and ECHA (2011), concerning the scope of the REACH regulation in relation to waste.

[51] ECJ judgement (C-358/11 - Lapin luonnonsuojelupiiri) on a Finnish Supreme Administrative Court preliminary ruling in July 2011 has implications for the reuse of hazardous waste and the application of Annex XVII of REACH across the EU. (ECJ 2013).

The National Waste Plan (FE, 14/2009) (MoE 2009) is a nationwide strategic plan; specifically, it aims at preventing waste generation and reducing harmful health and environmental impacts of waste, including the creation of enabling conditions for increased recycling and higher material efficiency. New focus areas cover steering waste streams into preferred activities in line with the waste hierarchy, clearer guidance on the definition of waste and further development of producer responsibility. New waste prevention steering methods are also more focussed on the design and production phases with increasingly voluntary, agreement-based, joint approaches and market creation instead of direct regulatory control. Further, material efficiency including efficient use of raw materials has become a major legislative issue in this context (Suvantola and Lankinen 2008).

Market-based instruments such as taxes offer several advantages as a means of achieving environmental objectives by, for example, influencing prices (through taxation or fiscal incentives), and they give companies a longer-term incentive to pursue technological innovations that further reduce harmful impacts on the environment. In this respect Finnish landfill charges and the national waste tax, including the possibility that they will increase in the future, have prompted waste recovery in some industrial sectors (Kautto and Melanen 2004). Taxes and fees related to wastes are generally included in legislation on taxation, although some fees are included in waste legislation. The Finnish Waste Tax Act (1126/2010) covers not only public but also private landfills, where a tax is levied on all waste deposited at landfill sites that have reuse and recycling potential and by imposing it, waste producers can be encouraged to find alternative non-landfill residue management options.

Finland's Environmental Protection Act (86/2000) and Decree (169/2000) (MoE 2000) regulate processes that may cause damage to the environment with the relevant objectives of prevention of the generation and harmful effects of waste and promotion of sustainable use of natural resources (e.g. in relation to environmental permits for process industries). Under the permitting regime, material efficiency (MEf) can be improved by residue utilisation covering the creation of new by-products. In Finnish legislation the mandate is stronger than at the EU level and has been streamlined in the process of revising the new Waste Act (646/2011).

Residue utilisation and waste status

At present the only procedure for utilising residues [other than specified residues such as coal, peat and biomass derived ash or crushed concrete (VNa 2006a)] is where the operator of specified recovery processes holds an environmental permit [Environmental Protection Act (86/2000)] to engage in the professional processing of waste. The permit must contain the necessary conditions on waste types and its management to ensure compliance with the Waste Act (646/2011). A permission granted to process waste under a permit may be restricted to certain types of waste and if necessary, the permit can specify that the operator may only process waste originating from a certain area. Once a residue is produced, then replacing the waste status of a material with a non-waste by-product status can be crucial for a material's subsequent recovery. Typically, changing the waste status means that a company needs to apply for a new environmental permit. Industrial actors apply for environmental permits through a process that contains several stages where the environmental regulation authority and the general public assess and evaluate the application. In cases where no objections are filed against the permit application, the environmental authority can issue the permit without a court decision. However, if a complaint is filed during the evaluation period, the permit process is transferred to an administrative court. Should the permit evoke further complaints after the court decision and after the applicant has revised the application, the permit process is then transferred to the Supreme Administrative Court (SAC).

Finally, the SAC often turns to the ECJ for statements and recommendations on whether a given substance can be treated as a by-product instead of a waste.

The MOTIVA Initiative

As part of Finland's national programme to promote sustainable consumption and production, the Ministry of the Environment and the Ministry of Employment and the Economy set up a material efficiency (MEf) centre under the auspices of MOTIVA, an agency responsible for promoting efficient and sustainable use of energy and materials on a national level, that will provide services for businesses and advice for consumers and public sector organisations on various ways to improve material efficiency (MOTIVA 2010). The MEf unit of MOTIVA assists in the promotion of material efficiency in companies, public administration and households. The focus of the initiative is to create wellbeing by promoting the use of energy and materials that are as harmless to the environment, and as productive as possible, through industry expertise in issues of energy and materials efficiency. Practical arrangements to achieve these aims are provided through advice and services on energy and materials efficiency including audits and tools, energy efficiency agreements and sustainable technology procurement. A voluntary MEf auditing scheme is currently being prepared by MOTIVA which also has a wider remit concerning renewable energy and linkage with the national energy and climate strategy to increase the use of renewable sources of energy and their share of energy consumption.

Although MOTIVA has a consumer focus in terms of energy advice, there is no specific consumer-orientated waste focus or waste prevention and minimisation role, with all material/resource efficiency efforts being focussed on producers. However there is no formal linkage with environmental permitting authorities in areas such as process industry regulation, waste prevention or waste minimisation.

3.9.5 Sustainability management

Sustainability management, in the form of the synthesis of sustainability aspects with business and community management, is also increasingly becoming part of strategic management latterly and thus it receives an increasing amount of attention as an external and internal driver of sustainable industrial development (Boons et al. 2011; Tingström et al. 2006). Perhaps the main issues and key challenges associated with management approaches that can encourage progress in sustainable industrial development relate to finding new more holistic paths forward. Companies can gain many benefits through sustainability management including better economic environmental performance based on efficient use of resources, materials and energy, an improved public image, as well as better fundamental business sustainability. Through encouraging and developing these elements they can be translated into competitive advantage. Notwithstanding the general environmental sustainability perspective and the spin-off business advantages it can offer, there is also the issue of fundamental or true business sustainability, in other words the ability of the form of a particular industry, technology or business approach to continue in the medium to long term with respect to its energy and raw material demands, process and product environmental impacts and markets for its products. The ability of businesses to be strategic rather than reactive in their outlook means that they may be more able to anticipate future pressures and the competitive advantages that could arise. This is addressed in more detail in Section 4.2.3.

The EU advocates sustainable development and associated approaches to sustainability in all sectors of European development. This implies that companies can gain competitive advantage by adopting a proactive approach to sustainability management in accordance with the changing operational environment.

4 Synthesis of publications and discussion

The use of process industry residues for the development of novel residue-based products for use as ameliorants for land conditioning or as construction materials, are utilisation options that allow the synergistic combination of inter-industry flows. Approaches such as these would contribute to more closed material cycles across wider systems and also encourage the formation of totally new processes in the industrial network.

Research results are presented and discussed in relation to the main themes and case study research on residue-based symbiosis product concept utilisations. Taking a more holistic approach to the subject of beneficial utilisation of process industry residues required a non-standard research methodology, which in turn demanded a more expansive and eclectic[52] approach to the focus of research publications. In this respect this is a new way to addressing these issues and helps advance the solving of sustainability problems through multidisciplinary approaches; cf. Research Methodology Section 2.1.

Residue characterisation and utilisation potential case studies of combined residue-based concepts for engineered symbiosis products, including consideration of the institutional barriers and drivers involved in moving eco-efficiency ideas forward locally, are all reported. An overarching assessment of the role for institutional aspects is also combined with a broader assessment of the values of the ecological metaphors we are attempting to apply and the normative aspects involved.

Given the depth and breadth of the themes discussed in this work, this section also explores and discusses additional ground to that presented in the published articles, which by their nature were depth constrained.

Institutional aspects

Papers II, III, IV and **V** explored how under the current system, the process of removing the waste status of a material tends to be a time-consuming and expensive process for all actors involved. The new Waste Framework Directive (WFD) (EC 2008c) in particular offers the possibility to develop a more straightforward approach to the promotion and use of new residue-based products, however there is still a lack of clarity in the application of waste definitions. These papers further assessed whether the existing institutional framework for the utilisation of inter-industry residues create institutional barriers which may lead to unsustainable practices and addressed the issues of successful product development and the need for an enabling institutionally aligned environmental approach that includes appropriate market incentives and regulatory instruments. The papers gave recommendations for overcoming these barriers. These recommendations included the design of new approaches that support industrial symbiosis and contribute to progress towards more sustainable societies, including enhanced focus on creating an enabling institutional environment for industrial innovations, the promotion of material efficiency through incentives policies and regulations, and guidance in the form of *soft law* on novel uses of materials and closure of resource cycles. The rationale of these studies was based on the idea that the existing institutional framework for the utilisation of inter-industry residues may erect institutional barriers, which may lead to unsustainable practices that serve the interests of neither the industry nor society at large. Additionally, **Paper VII** reviewed selected resource, waste and product related policy and legal instruments of both the EU and

[52] *Eclectic* – following multiple systems, selecting and using the best elements of all systems.

Finland in order to identify potential constraints for these goals, and the specific implications arising from their implementation, as well as suggesting some next steps in the development of industrial residue-based symbiosis products.

Residue characterisation and utilisation aspects

Paper I introduced the hypothesis that forest and carbon steel industry residues could be utilised in the manufacture of residue-derived materials that could be beneficial in amending agricultural or forest soil properties, such as increased acidity or potential lack of vital nutrients. The paper provided background to the operations of these separate industrial sectors, with a suggestion of relevant candidate facilities, and also discussed the broad characteristics of individual residue streams. The integration of selected steel making slags with pulp and paper making residues (fly ash, paper mill sludge, as aggregate and green liquor dregs and lime wastes as alkaline components) to make more sustainable forest soil amendment product concepts (a soil amendment matrix pellet) and the investigation of product characteristics was thus the next step. The concept of symbiotic cooperation of two formerly separate industrial sectors that could enable the utilisation of waste-labelled solid residues in manufacturing novel residue-derived materials technically and environmentally suitable for replacing virgin commercial alternatives was investigated. The contention that utilisation of process industry residues such as steel making slags and residues from the pulp and paper industry provides possibilities to produce symbiosis products that can be utilised legally was then investigated in **Paper V**. The potential for symbiosis concepts to be used for soil amelioration pellet manufacture are reported in view of the issue of heavy metal concentrations in various pellet matrix formulations. The advantages of symbiosis products in terms of reduced energy consumption and avoidance of environmental impacts caused by increasing landfilling and their role in advancing more sustainable management of natural resources were then researched further and reported in **Paper VI**.

These results are now presented, explored and discussed in more detail.

4.1 Symbioses product concepts - Case studies

In **Papers II, III** and **VI** synthetic product concepts conceived in **Paper I** and based around the symbiotic utilisation of residues from the steel, pulp and paper industries were developed further and used as case studies. One of these case study product groups was used in the assessment of the development potential of such concepts from a general environmental sustainability perspective **(Paper VI)** (**Figure 19**). Here the focus was on testing the concept against legal requirements and policy objectives, and determining how to assist and promote the development of such process industry residue-based products through co-operative and joint design of appropriate incentives, policies and regulations.

The industrial symbiosis (IS) product concepts or cases that form the foundation of the study in **Paper VI** encompassed the utilisation of inter-industry solid residues from around the Bothnian Arc. A range of product concepts were presented:

- A soil amendment/amelioration pellet formulation.
- A non-engineering standard low competence concrete formulation.
- A mine filler/solidification matrix.

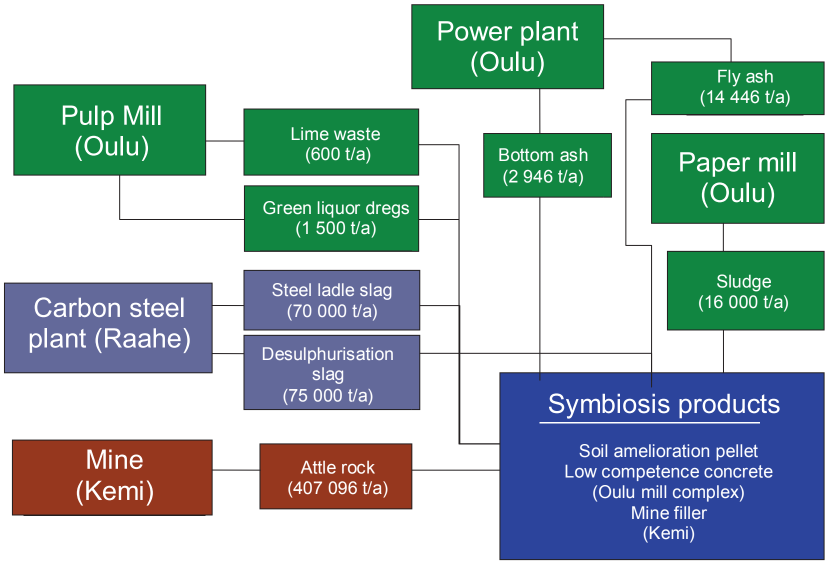

Figure 19 *Case Study - Steel, pulp and paper residues (modified from Paper III)*

Soil amendment products

The soil amelioration pellet concept would have a solid slow release matrix designed to return nutrients to soils and would consist of steel industry derived ladle slag and combustion derived fly ash (binder), paper mill sludge (aggregate), lime residues (alkali) and water as described and performance tested (amongst other formulations) in previous work Mäkelä (2012), Mäkelä et al. (2010; 2011; 2012a; 2012b). The final objective is that nutrients might be returned to forest soils.

Filler products

The other two symbiosis products are still hypothetical cases at this point in time. The residue-based concrete would consist of steel ladle slag and fly ash (binder) plus steel desulphurisation slag and combustion derived bottom ash (aggregate) and water, and be used to make low competence street furniture or used as structural backfill. The mine filler concept would be based on a mix of attle rock (a bulk mining residue), steel ladle slag, fly ash and water and it could be used in large quantities to replace expensive Ordinary Portland cement based formulations currently used to fill in empty mine cavities to solidify backfilled voids as a final step in mining operations.

Specific formulation for soil amendment

A further specific product concept formulation was investigated in **Paper V** in relation to the possibility of combining desulphurisation slag, fly ash, paper mill sludge and lime waste into actual manufactured pellet products and the analysis of relevant physicochemical properties, easily available plant nutrient concentrations and trace element availability and hence their likely performance characteristics.

4.2 Addressing barriers and encouraging drivers

4.2.1 EU policy and legal instruments

Increasing the sustainability and environmental performance of modern process industry calls for inter-industry residue utilisation and novel symbiosis products. Overall, this is in line with the *waste hierarchy*, but the realistic possibilities of such reuse may be dependent on whether the residues are regarded as waste or products. An excessively wide interpretation of the definition of waste imposes unnecessary costs on the businesses concerned, and can reduce the attractiveness of materials that would otherwise be returned to the economy. An excessively narrow interpretation could lead to environmental damage, and undermine waste law and common standards for waste in the EU (COM(2007) 0059 final) (EC 2007). Once a residue is produced, then replacing the waste status of a material with a non-waste by-product status can be crucial for a material's subsequent recovery.

The potential institutional barriers that have to be addressed and the general drivers that need to be promoted for the development of industrial residue-based symbiosis products within the EU policy and legal framework identified in **Paper III** are shown in **Tables 2** and **3.**

Table 2 *EU policy instruments - a summary of implications for development of symbiosis products - Paper III*

Policy Instrument	Identified potential institutional barriers	Suggestions on how to bridge the specific institutional barrier
Sustainable development strategy	Lack of guidance on the design and practical implementation of integrated, coherent and cross-sectoral approaches to sustainable production and product design	Institutional changes to integrate sustainability principles into policy-making and better regulation in a coherent way
Integrated Product Policy (IPP)	Lack of guidance on the practical implementation of comprehensive approaches and related approaches to product life cycles	New institutional focus on life cycle thinking and particularly on the environmental performance of products throughout their whole life-cycle and promotion of wide application of LCA
Integrated Industrial Policy (IIP)	No information on the practical measures to address the whole value and supply chain in an integrated manner	Creation of institutional support for local level measures to integrate the whole value and supply chain with special emphasis on recycling and material and energy efficiency
Ecodesign	No information on the practical measures to prioritise environmental performance of products during their whole life cycles (life cycle perspective)	New institutions for local level measures to apply life cycle perspective covering whole product life cycles
Thematic Strategy on the Prevention and Recycling of Waste	Lack of 1) guidance on the application of life-cycle thinking to waste management and on the life-cycle approach to resources and materials, 2) minimum standards for recycling activities and recycled materials and 3) information on the utilisation of waste as a valuable resource to be recycled for further use and on ways to avoid landfilling	Institutional development to: establish 1) quality standards (covering, e.g. minimum standards for recycling activities and recycled materials) for recycling to promote demand for and acceptability of recycled materials and direction of waste flows towards recycling and re-use, and 2) life-cycle thinking and approaches (focus on waste management)

Legislation is one of the main drivers in improving material efficiency, but it may also become one of the main barriers as seen in the residue or waste or by-product question.

Table 3 *EU legal instruments - a summary of implications for development of symbiosis products - Paper III*

Legal Instrument	**Identified potential institutional barriers**	**Suggestions on how to bridge the specific institutional barrier**
Waste Framework Directive (WFD)	Lack of guidance on the practical implications of: 1) EoW legislation and criteria for symbiosis products (product systems with multiple residue streams) and 2) the waste hierarchy (focus on life-cycle thinking and prioritisation of the prevention of waste generation and recycling/recovery operations over disposal)	Development of enabling institutions for the effective implementation of a 'recycling society' encompassing further development of the EoW legislation and criteria for symbiosis products (e.g. EoW status in a recovery operation encompassing the use of multiple substances as secondary raw materials) and more emphasis on life-cycle approaches and overall sustainability
REACH Regulation	Lack of guidance on the possible implications for industry (e.g. possible bulk residue streams with potential to be used for product manufacture - REACH applies if not waste?)	Clear institutional status of: 1) highest volume residue streams likely to be utilised as raw materials (process industry streams of stable composition) and 2) low volume, low value residue-based products as 'articles'
Industrial Emissions Directive (IED)	IED focuses on the operations of industrial installations (reduction of emissions) and not on their products despite obvious waste and EoW aspects associated with products Lack of guidance on: 1) practical implications of an integrated approach encompassing material efficiency (raw materials), waste management, emissions, energy efficiency and BAT/BREF documents, 2) the general obligation of the operator of installations to advance recycling and waste prevention (in accordance with the WFD) and 3) how to address the environmental performance of an industrial plant as a whole in environmental permits	More material, resource and energy efficiency guidance under IED – i.e. additional horizontal technical guidance on best available techniques (BAT) for resource, material and energy efficiency and waste minimisation (what are implications for environmental permit applications?) Development of institutional setting for: 1) an integrated approach encompassing clear reference to material efficiency (raw materials), waste management, emissions, energy efficiency and BAT/BREF documents, 2) recycling and waste prevention procedures (in accordance with the WFD) for the operator of installations and 3) the environmental performance of an industrial plant as a whole in environmental permits
Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers	Unclear market status of fertiliser products and/or substances manufactured from multiple industrial residue streams (symbiosis products designated as 'EC Fertiliser'?)	Institutional development for more clear market status of fertiliser products and/or substances manufactured from multiple industrial residue streams (symbiosis products designated as 'EC Fertiliser') encompassing technical rules covering: 1) definition and composition of fertiliser types, 2) identification, traceability and marking and 3) nutrient content tolerances and other fertiliser requirements such as indication of the nitrogen, phosphorus and potassium content of fertilisers placed on markets of EU Member States

These results outline the practical implications of both EoW legislation and criteria for single residue streams and symbiosis products (product systems with multiple residue streams) and the waste hierarchy covering new focus on life-cycle thinking and prioritisation of waste prevention and recycling over disposal to a landfill. The waste status of materials is dependent on the interpretation of the definition of waste in the WFD. One important subsequent question is also whether the REACH Regulation would apply to such residue-based symbiosis products if they are no longer legally classified as waste.

In general, the results suggest that lack of a comprehensive and integrated approach to the environmental performance of industrial plants (in the context of environmental permits for example) may also create institutional barriers to the development potential of symbiosis products. For the specific case of soil amelioration pellets (one of our synthetic test case products), the market status of fertiliser products and/or substances manufactured from multiple industrial residue streams is unclear for example.

The findings suggest that the integration of sustainability principles into industrial decision-making and policy making with an emphasis on promoting sustainable production and product design is also among one of the key focus areas for institutional development. Additionally, product life cycles and particularly the environmental performance of products during their whole life cycle, as well as related aspects covering the whole industrial value and supply chains, need to be addressed in a more holistic manner.

These issues are now reported and discussed in more depth than originally presented in published papers.

Impact of the Waste Framework Directive and End-of-Waste (EoW) criteria

Within the EU the renewal of the Waste Framework Directive (WFD) (2008/98/EC) has implications for the recycling of industrial residues. **Papers III** and **IV** ask if the updated directive really makes things more straightforward or whether there are now new challenges for those seeking to utilise such materials.

The focus here was process industry residues in relation to their potential as suitable materials for the manufacture of novel residue-based symbiosis products in Finland.

The questions this paper addressed were:

- How does the WFD change the playing field compared to the previous state of affairs?
- Do these changes help to remove or ease known obstacles to re-use and recycling?
- What new difficulties or questions now arise due to the new legislation?

The legislation's primary object has been - and will also be in the future - the minimisation of negative effects and risk to human health and the environment. Sometimes this primary aim has led to contradictory situations where efficient use of valuable waste materials is difficult due to waste legislation provisions. It has been claimed that the definition of waste may even be an obstacle for re-use and recycling because of the costs of complying with waste legislation (Salmi et al. 2011) and also highlighted in **Paper IV**.

The rather tight interpretation of the definition can be justified with environmental concerns and the benefits of additional control[53]. Nevertheless it was seen necessary to develop new solutions to promote recycling and re-use.

The following aspects of the WFD also call for some attention in relation to the focus and importance it gives to areas that would more fully support real attempts to improve resource efficiency.

Waste prevention - Although *waste minimisation targets* failed to be included in the WFD, there have been some significant developments in this area. Notably, EU Member States are now required to establish waste prevention programmes in their waste plans or environmental policy programmes by 12th December 2013. Although the WFD does not contain any qualitative or quantitative targets there is a requirement for these to be set in national programmes. Perhaps the most encouraging aspect of this requirement was the stated aim of such prevention objectives and measures to be aimed at breaking the link between economic growth and the environmental impacts associated with the generation of waste (EC 2008c).

Quality of recovered product is not adequately addressed - When recovery is discussed, the WFD requires three main aspects should be taken into account:

- How effective the method is in terms of recycling rates,
- What the environmental impacts of the recovery action are, and
- What the quality of the product generated by the recovery action is.

The first point has been the most dominant in the on-going discourse. In recent years the second bullet has also been recognised more and more. The WFD's most significant change is the introduction of an environmental objective which focuses the WFD on the reduction of environmental impacts from waste and waste management. This third bullet point remains somewhat neglected except in a few cases such as the UK WRAP Quality Protocols approach which is designed specifically to address this (see Section 4.2.2).

Down-cycling is defined as a recycling process in which all or part of the material from a waste product is used for a product with lesser material property requirements as the previous one and in reality this is what happens in the majority of cases where wastes are contaminated. Of course recycling can almost never be complete in the sense that all materials could be kept in the cycle with no quality decrease and there are generally recognised thermodynamic limits to what is achievable. The WFD does not provide much help here since in principle it is contrary to the waste hierarchy not to recycle something that could be recycled, but in practice the present environmental instruments cannot address this problem.

Incentive to use all available economic instruments - One of the major reasons for under-utilisation of some wastes and residue resources is that there is no immediate market incentive to do so. In other words: it can be cheaper to landfill waste than to go through a recovery or recycling process. It is a two way problem: either the virgin raw material is not expensive enough or landfilling is too affordable[54]. This dilemma calls for economic instruments and here the WFD does encourage the use of such instruments[55] and especially at national level since economic instruments are more easily deployed at that level[56]. This is appropriate since Community legislation on

[53] COM(2003) 301 final, p. 38.
[54] Of course landfilling could also be totally banned by a regulatory measure, but this would not be simple as disposal may still be the only acceptable option in many cases.
[55] WFD, Preamble 42, p.7.
[56] *Ibid*., p. 9.

taxation needs to be unanimously decided - which would be problematic at a higher level. However, in reality it is often just as difficult to introduce economic instruments on a national level as this can sometimes place the implementing country's own industry in a disadvantaged position competition-wise and in terms of timing and possible regulatory arbitrage[57] effects.

Prevention at the top of the hierarchy - what does it mean? - It has been claimed in the literature that broadly defined waste prevention also comprises the reduction of harmfulness of waste – not only the quantity of waste (Laner & Rechberger, 2009). This is so called 'qualitative' waste prevention. What has not usually been widely discussed however is whether such qualitative waste prevention may or may not lead to an increase in the *amount* of waste. The definition of a *by-product* can possibly solve this dilemma because if a modification to a process leads to an increased side-stream that is considered to be a by-product, then the definition of waste can be avoided and the acceptability of the increase is not an issue anymore; cf. Lilja et al (2011) .

Waste prevention can in practice be optimisation of material use or energy intensity or reduction of the use of harmful substances; substitution means a change in input flows that generate the same outcome; product re-use is use of product in its original form with or without reconditioning (Laner and Rechberger 2009). Pongrácz (2002) sees that waste prevention can be divided into four subclasses: using less material to produce a product, also referred to as waste minimisation (Phillips et al. 2001), creating durable products, waste evasion and using less harmful substances. Here, waste evasion could be a change in production process that leads to a lesser amount of waste or it could be (immediate) utilisation of created waste so it would no longer be waste (Pongrácz 2002). Recycling within an industrial system's boundaries, could possibly be seen as prevention in this way of thinking, this implies that even processes that traditionally should be understood as recycling could be interpreted as prevention (Laner and Rechberger 2009). From a legal point of view this thinking is not at all simple. In practice environmental permit authorities tend to focus on what happens to the material stream. In Finland, if material stays in motion (e.g., by pumping) then it would not turn into waste, but if it is put into a tank it would be considered waste for example. Of course, after having become waste, its management can no longer be termed prevention. It can be seen that definitions of waste/by-product and prevention/re-use/recycling are heavily coupled therefore; cf. Pongrácz (2002). If something is considered prevention it would avoid being defined waste and no by-product or EoW definitions would be needed.

It is also important to note that the waste hierarchy is also coupled to the *proximity principle*: if something is deemed to be re-use or recycling then the proximity principle would not have an effect, but if it were to be deemed to be disposal then the waste should be treated somewhere in the vicinity to the place where it is created.

Waste *minimisation* would entail preventive actions plus recycling and sometimes incineration, so it has a broader scope but no legal status as such. In reality the distinction between waste prevention and waste minimisation can therefore be challenging. This issue is explored more in Section 4.2.2 in relation to material efficiency (MEf) and best available techniques (BAT).

End-of-waste (EoW) criteria - The EoW criteria have been formulated in order to clarify when waste ceases to be waste and can be dealt with as recovered material freely traded as such in the open market. This is expected to facilitate and promote recycling, ensure a high level of environmental protection, reduce the consumption of natural

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[57] *Regulatory arbitrage* - capitalising on differences between regulatory systems in order to circumvent unfavourable regulation, e.g. in relation to geographic relocation of activities.

resources and the amount of waste sent for disposal (JRC 2009). The EoW criteria are constructed from a waste-stream perspective.

In the WFD, the general definition of waste is supplemented by the concept of by-product (art. 5) and *end-of-waste* (EoW) criteria (art. 6). Before the renewal of the WFD in 2008 these concepts were merely based on case law of the European Court of Justice (ECJ) which has interpreted the definition of waste in numerous decisions[58]. This case-law still remains relevant; cf. Elonova et al. (2010), but the definitions have also been incorporated in the directive. The WFD outlines that a substance can be considered a *by-product* as long as its further use is certain and lawful, it can be used directly without further processing other than normal industrial practice, and it is produced as an integral part of the production process.

The categories of waste that the new WFD recognises as candidates for the development of EoW criteria include construction and demolition waste, some ashes and sludge, scrap metals, aggregates, tyres, textiles, compost, waste paper and glass. The new WFD EoW criteria will therefore make it possible for EU Member States to define in an environmental permit or general binding norm that certain by-products have no adverse environmental or human health impacts. This means that EoW criteria can to some extent be decided at national level via domestic legislation. In exchanges between EU States this could be problematic if (for example) in the Bothnia Arc region (Sweden and Finland) there could be regulatory differences in the application of EoW criteria to different residues. However, the industrial residues used in the proposed symbiosis products (**Papers I, V** and **VII**) are defined as wastes in accordance with the WFD. The feasibility of utilising the material is therefore influenced by the prerequisites for losing this waste status (through the prerequisite status that waste has undergone a recovery operation e.g. pellet production) and for applying product based legislation to the potential product instead. The prerequisite of losing waste status (i.e. potential for obtaining EoW status concerning the use of a substance or object) depends on it leading to no overall adverse environmental or human health impacts. Pellet production from residues would probably fulfil some of the essential EoW criteria for losing waste status therefore. See Section 4.3.2.

In any case, losing waste status and subsequent application of product-based legislation to potential industrial symbiosis products requires further legislative development. Although recycling and reuse of residual materials defined as waste (WFD art. 3) is possible under the waste regime, there are limitations to this. Waste regulation does not define the legal prerequisites under which utilising residues in such novel concepts as introduced in this study would be possible, nor how waste status could be lost and product based legislation be applied to the potential products instead.

In addition to the WFD's EoW criteria it is now possible for Member States to define in an environmental licence or general binding norm that certain by-product presumably has no adverse environmental or human health impacts[59]. This means that EoW criteria can to some extent be decided on national level and this is how, for example, the UK is going about determining a list of priority waste streams for criteria development. See Section 4.2.2.

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[58] See ECJ decisions C-9/00 Palin Granit Oy, C-444/00 Mayer Parry, C-114/01 Avesta Polarit Chrome Oy, C-235/02 Saetti and Frediani, C-457/02 Niselli, C-317/07 and C-209/09 Lahti Energia Oy. The ECJ has stressed in its decisions that the definition of waste must be interpreted widely and a material that is actually 'discarded' must be considered as waste. Still, the decision as to whether a material is waste or not, must be taken by the competent authority on a case-by-case basis focusing on the factual circumstances; see (Eloneva et al. 2010) and (EC 2007).

[59] WFD, Preamble 22.

One can also note that the EoW requirements resemble the old criteria for *not* defining something as waste. The dilemma might therefore in the future be the following: as the process for defining EoW criteria is also rather cumbersome, operators might first try to seek a legal decision on whether something is considered to be a waste or not. If the decision places the stream as waste, a process for achieving EoW is then launched. But will it be an option, as the requirements seem to be more or less the same in each case?

REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals

From the point of view of environmental protection and health targets, the WFD and REACH frameworks complement each other. The fulfilment of product-based legislation and standards aiming at, for example, safeguarding human health targets, is one of the essential criteria when considering premises for losing waste status and utilising residual materials in novel product contexts.

The regulatory and cost burden of REACH could apply to residue-based industrial symbiosis products (to soil amelioration pellets for example) because they are manufactured as new products and it could also apply to residues as by-products if they are imported or placed on the market by themselves. REACH may therefore be applicable if the substance/product loses this waste status and is no longer covered by the WFD (ECHA 2012). It applies to the use of substances during relevant parts of their life-cycle, and in the context of recovered substances and waste, all forms of recovery may be considered as a manufacturing process (the output or result is one or several substances, or a mixture, or an article that have all ceased to be waste.) The recovery process may produce new articles, and registration of substances in an article is required if they are intended to be placed on the market under conditions specified in REACH.

Papers III, IV and **VII** addressed this major question concerning whether the REACH Regulation would apply to residue-based symbiosis products if their creation makes them no longer legally classified as waste. Since symbiosis products are by their nature likely to be reliant on the specific local nature of residue streams and made in relatively small quantities, this issue is likely to be almost always case-specific. Since REACH costs act as a barrier, the size of a residue-based product's market might mean that the residue raw material waste status and subsequent treatment via an environmental permit path could still be the preferred approach.

Thus the main finding is that manufacturers of potential symbiosis products need information on the implications of REACH for product systems with multiple residue streams covering: the EoW status aspects, broad exemptions for low hazard mineral type substances and articles and treatment of high volume residue streams for example.

Fertilisers and construction agents

The main findings of **Papers II-VI** were that it would be ecologically preferable, if these solid residues (as examples) could be suitably formulated, processed, and then safely returned back to agricultural and forest ecosystems as a fertiliser/ameliorant, or reused as construction agents for example. Such an approach would both conserve virgin materials, return nutrients back to ecosystems and could be an example using industrial residues to bolster the sustainability of agricultural and forestry practices and help further improve the eco-efficiency of the forest and steel industries.

Further institutional development in terms of specific rules for residues and symbiosis products for use in land amelioration would assist here and help address the market status of such residue-based products if they could be designated as *EC Fertiliser* (EC 2003d), i.e. fertiliser products from single residue streams and/or substances manufactured from multiple industrial residue streams encompassing technical rules for their quality control and use/application.

4.2.2 Other institutional aspects

Papers II, III, IV and **VII** addressed some of the institutional aspects where new research and development needs to be focussed on the systemic investigation of the evolution of institutional capacity over time in regional industrial systems, since (capacity building) in legal and policy context may contribute to reduced ecological impact of regional systems.

In this regard the creation of additional institutional aspects such as new economic instruments, the use of so called *soft law* for the creation of institutional initiatives to coordinate effort to find solutions to issues would be beneficial. For example, EoW criteria development at local levels, encouraging increased industrial residue utilisations in general and use of environmental permitting regimes to assist with material efficiency improvements in the process industries, are areas that require a more integrated approach designed around the idea of removing barriers and strengthening drivers for increased environmentally beneficial residue utilisation. Here, according to Melanen et al. (2002) the use of economic instruments could also be extended and directed towards material efficiency and especially efficient use of natural resources to aid the recycling of industrial residues.

The research was accomplished through interviews of actors in both operational and environmental management within Finnish process industry and a review Finnish legislation and initiatives such as the Finnish MOTIVA initiative which promotes material and energy efficiency on a national level in Finland (MOTIVA 2010), and of the UK based Waste & Resources Action Programme (WRAP) that aims to help support and develop recycling in the UK and to create a market for recycled materials (WRAP 2012).

Quality protocols - UK WRAP

An outline of a useful model for approaching the institutional changes to achieve better resource efficiency is discussed in **Paper IV** in the form of the UK based WRAP initiative (WRAP 2012). This initiative aims at promoting sustainable and efficient use of materials focussing on the examination of EoW approaches and the use of *quality protocols* that guide residue recovery. The main priorities and aims of the UK's initiative relevant to this discussion are that it: aims to help prevent waste production and encourage sustainable resource use, accelerate resource efficiency especially though facilitating increased recycling through creating efficient markets for recycled materials and products, whilst removing barriers to waste minimisation, re-use and recycling.

The WRAP approach also plays an additional strong role in upstream activities related to process industry wastes and residues regulated by the UK environmental permitting authorities (i.e. The Environment Agency in England and Wales, and the Scottish Environmental Protection Agency). The idea that markets are the key to resource recovery is central to the overall approach adopted in the UK and this is seen clearly in the residue quality protocols that have been developed to aid in maximising benefit from unavoidable wastes.

Use of Waste Protocols

The *Waste Protocols Project* is a joint UK environmental permitting authority (Environment Agencies) and WRAP initiative in association with industry. This initiative seeks to achieve production of quality protocols that clearly set out the steps that must be taken for a waste to achieve non-waste status (i.e. achieve the EoW criteria), to become a non-waste product or material that can be either reused by business or industry, or be supplied into other markets, enabling recovered products to be used without the need for waste regulation controls. In essence, a quality protocol gives guidance on how to recover waste, remove it from the environmental regulatory regime and therefore avoid unnecessary regulation.

The individual protocols are developed in partnership with UK environmental protection authorities (permitting authorities), WRAP and affected industries, and consist of a detailed technical description of the origin and characteristics of residues and the quality criteria against which their use in subsequent applications may be allowed if the materials attain the stated quality standard. Examples of successful utilisations of residues in residue-based products are described as well as their limitations. The benefits in terms of reduction in landfilled waste and the financial cost savings are also estimated, as are the greenhouse gas emission and virgin resource savings. A detailed technical report and financial impact assessment are then produced for each protocol and the final step is the production of a *regulatory position statement* which acts as a form of *soft law* that defines the status of residue materials that achieve EoW status and under what circumstance waste management controls no longer apply to it (WRAP 2010).

As examples of the types of materials targeted recently the UK quality protocols developed so far include protocols for the production and use of: compost from source-segregated biodegradable waste, aggregates from inert waste, processed glass cullet from waste flat glass, secondary raw materials from waste non-packaging plastics, biodiesel derived from waste cooking oil and rendered animal fat, anaerobic digestate, tyre-derived rubber materials, pulverised fuel ash and furnace bottom ash, as well as gypsum from waste plasterboard. As such, these materials are either high volume or have specific characteristics that make them priority targets (for example the Landfill Directive's pressure on organic wastes disposal as a driver in the case of the compost protocol or high calorific values for other organics, and high volumes in the case of ashes - the largest industrial waste stream in the UK). Criteria for EoW in the production of aggregates from inert waste, the production and use of products from fully processed waste derived wood and poultry litter ash and paper sludge ash are pending UK public consultation. A further four waste streams are now also being looked at namely: treated ash from the incineration of poultry litter, feathers and straw, non-virgin wood from post-industrial and post-consumer sources, televisions, computer monitors and compressed tyre bales (WRAP 2010).

As **Papers I, III** and **VI** discuss and show, the act of manufacturing a product from residue materials would, from a life-cycle perspective, improve the material efficiency of industrial processes in general by virtue of the conservation of virgin resources and this would clearly contribute to the sustainable use of natural resources (see Section 4.3). However, the new EoW criteria incorporated into the WFD do not apply in cases where the potential product consists of several residues, so in order to further develop the EoW legislation towards a regulation model more effectively incorporating a product-focussed and innovation orientated approach to resource conservation and waste management, the criteria would need to be extended to cover a full range of recycled products independent of their raw material sources and their residue streams. This has system boundary implications that are problematic in legal terms, since even where useful residue-based products can be made from industrial residues the streams may be waste at law until they are combined in symbiosis products – this seems counter-productive.

Industrial residues may not be waste in a legal sense if the holder (mill or plant) does not intend to discard them, but, for example, the holder manufactures something out of them or delivers them to a nearby plant for further processing, such as for use in potential symbiosis products jointly with other residue materials. However, the legal interpretation of possible product, by-product, EoW or waste status requires reflection on different aspects of precedents and consideration of at least the whole process of secondary raw material generation from multiple sources (where nothing is discarded and all flows serve a purpose within the wider network), the actual manufacturing of symbiosis products and the nature of their use as products covering environmental impacts and also broader sustainability aspects. Noticeable issues here also include product legislation and standards, application-specific technical requirements, demand status, existence of markets and of course any potentially adverse human health and environmental impacts.

The UK's waste protocols type approach would seem to offer a way forward in this respect. However, the case-by-case interpretation approach taken by the courts, when there are particular issues over waste status, still requires an holistic assessment of the overall situations at hand taking into account, for instance, local case-specific characteristics. An industrial symbiosis (IS) approach or *IS thinking* via the use of systems thinking and a life cycle perspective, can all be of major assistance in this context together with appropriate supply/value chain management and assessment. Of course costs and investment aspects are also key in this respect (e.g. incentives and implications of public steering instruments).

The possible linkage between MOTIVA and WRAP type approaches and their countries' large process industries is rather weak in both cases, with material efficiency (MEf) advice and audits most likely not taken up by process industries, since only tailored services to mainly small and medium sized enterprises is on offer. However, large process industries have their strongest linkage with environmental permit authorities and technical guidance through EU level best available techniques (BAT) technical reference notes (or BREF documents) designed to support integrated pollution control and the new Industrial Emissions Directive environmental permitting activities.

Best available techniques (BAT) and material efficiency (MEf)

The challenging part of addressing institutional aspects concerns its lack of predictability in delivering strong signals to push behaviour in a particular direction. For example with BAT under pollution prevention and control/industrial emissions legislation (IPPC/IED), there are no fast ways to pass current BAT through to operational plants due to time lags of capital investment and lock-in to current technologies; so although new technical innovations could be proven, both in environmental and economic point of views, there are significant delays in influencing changes in production technologies. Indeed there is also the argument that BAT, once adopted and installed, itself leads to lock-in delay to any subsequent improved techniques and in the past this has favoured abatement approaches over prevention ones (Cunningham 2000).

What appears to be missing, is a way to drive process industry towards treating residue streams as material flows that can and should be modified and controlled within the process in order to maximise their utility in subsequent steps both inside the process and also outside in partnership with other industrial network partners. The use of material efficiency (MEf) and industrial symbiosis guidance as *soft law* would aid in this substantially, either through EC guidance, such as BAT guidance for instance, or via subsidiary guidance produced at national levels. In this respect legislation and policy should push process industries to seek synergies in residue management through support for waste law test cases, the development of residue-based product quality protocols/standards and incentives for inter- and intra-industry cooperation and research on symbiosis products.

Here the concept of MEf is still seen as an issue of economic efficiency and not as an issue of environmental policy; for example, in the case of process industry regulated under the environmental permitting regime, environmental management systems (EMS) are often considered as totally voluntary and not seen as subject to formal BAT assessment. To utilise the possibility to apply MEf in environmental permits these barriers must be overcome. Here, according to Lilja et al. (2012), guidance to environmental permitting authorities and industry is recommended to be in the spirit of soft law. The mainstream approach will continue to rely on the economic motivation for encouraging material efficiency, but additional soft law approaches can assist here in delivering environmental policy goals, as described below.

Material efficiency and permits

Papers III, IV and **VII** also explored the issue of where a concept such as MEf stands in this respect - especially in the interesting case of large process industries that are controlled under environmental permitting regimes and who are encouraged to follow guidance on MEf (JRC EIPPCB 2001; 2012). The permitting regime under the system of IPPC [i.e. the Industrial Emissions Directive (IED) (EC 2010b)], requires permitting authorities to apply certain aspects of waste legislation to permit conditions, including waste prevention. The principle of primarily focussing on the reduction of the amount of waste produced and the harmfulness of waste is called waste prevention (WPr) and only includes processes that take place before something has turned into waste (Lilja 2009).

However, according to Lilja et al. (2012) the concept of MEf is a broader idea than that of WPr since not all actions that represent improving MEf can be classified as WPr. For example the preparation of wastes for reuse, waste recycling or recovery of energy from waste represent one group of strategies for improving MEf, but by definition they are not part of WPr. Similarly gaseous emissions are not classified as wastes and neither are wastewater emissions if they are regulated by other legislation[60]; so MEf actions that prevent material losses to air, soil or water do not qualify as WPr.

Therefore, some actions in line with the WFD in pre-emptively reducing the adverse impacts of generated waste on the environment and human health (i.e. reduced quantities and hazardousness of waste) and actions that reduce the content of harmful substances in other materials, are not classed as WPr. It is pointed out by Lilja (2009) therefore, that it is not semantically straightforward as to whether MEf also covers the qualitative aspects of WPr and suggests that the concept of MEf in environmental policy should be understood to cover also the qualitative aspects of materials selection and prioritisation so that MEf would also fully cover the qualitative aspects of WPr. Here, because MEf is not tied to the definition of waste, the concept is broader than WPr and there could be the interesting possibility of investigation into its application in upstream circumstances, e.g. in situations such as those where holistic multi-residue stream-based symbiotic product concepts are considered for instance, perhaps in the context of a wider installation controlled under environmental permit law (i.e. within IED).

[60] WFD, Article 2.

The concept of MEf is therefore broader than WPr (**Figure 20**) and some WPr actions that improve MEf could therefore be classed as MEf actions. The implication of this, according to Lilja et al. (2012), is that although the permitting process cannot regulate an installation's products [which are addressed by other policy instruments such as the Integrated Product Policy (IPP) (EC 2003b; 2010a)], the selection of raw material and chemical streams should be assessed in line with guidance criteria on BAT under IED (EC 2010b). One of the goals of the IED is the prevention of waste, so a mandate for MEf regulation therefore comes indirectly from the principle of BAT (as a minimum reference criteria to be applied) and which is now strengthened to an obligation under IED compared to the preceding IPPC regime (EC 1996). '*The consumption and nature of raw materials (including water) used in the process and energy efficiency.'* is also listed as an objective for assessment in the IED[61] and more importantly the status of BAT Reference Documents (or BREFs) have now been strengthened under IED such that so called *BAT Conclusions* will be criteria approved by the EC and applied as minimum criteria[62] in environmental permits (Puheloinen et al. 2011).

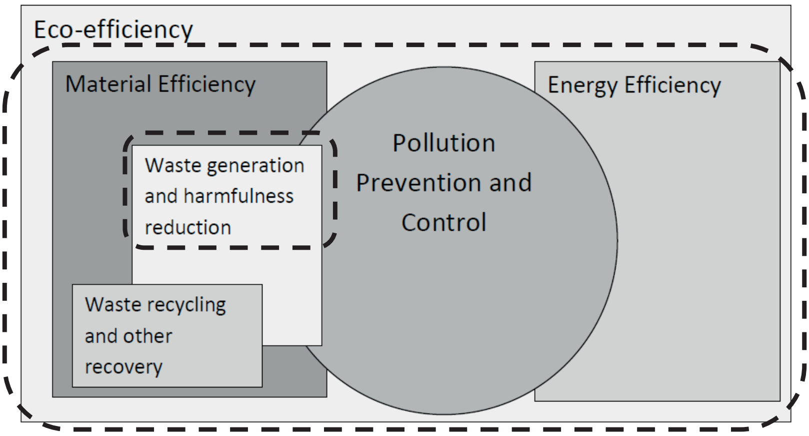

***Figure 20** Future BREF - Illustration of the overlapping of material efficiency and related concepts (modified from Lilja et al. 2011 and Lilja & Saramäki 2012)*

What this means according to Lilja et al. (2012) is that the mandate for MEf requirements that reduce production waste quantities, or their hazardousness, is strong. In this respect specific waste generation levels could also be listed in BAT conclusions as one set of emission limits. However, a somewhat weaker mandate is provided for MEf improvements that deal with material consumption that is not manifested in a generation of solid waste.

It is also important to note that neither MEf nor WPr has received significant attention in environmental permit procedures in Finland to date (Lilja 2008).

Resource efficiency BAT Reference Document - Under IPPC and IED, BAT reference documents [or BREF-documents; cf. JRC EIPPCB (2001)] could therefore now also encompass MEf aspects. The revision of process industry sector-specific BREF documents and guidance to reflect the need to more firmly answer MEf issues should therefore be addressed. An EC proposal[63] under IED to merge existing horizontal

[61] (EC 2010b) IED, Annex 3.
[62] *Ibid*., Article 14(3).
[63] Proposed work programme for the exchange of information under Article 13(3)(b) of the Industrial Emissions Directive (IED) (EC 2010b).

BREFs on energy efficiency and on industrial cooling systems, is currently being discussed with a renaming of this proposed merged BREF as *Resource Efficiency*. This move would open up a number of questions on the very wide scope of any such BREF document as well as the issue of translation of BAT conclusions into permit requirements. The introduction of this approach has already been questioned by industry however (Eurelectric 2012), in line with the view of Lilja (2008) that this could also limit the range of production technology choices for companies.

In general, there is a lack of information and guidance on many important issues such as the appropriate application of life-cycle thinking and on the life-cycle approach to overall resource, material and energy efficiency. To begin to look at a role for MEf in regulation under environmental permitting will have the useful effect of raising awareness of raw materials and chemicals selection as *carriers of environmental impacts* derived from the upstream part of their life-cycle. Similarly, downstream aspects might also be identified such as modifying process conditions to generate marketable by-products instead of residues falling to be managed as wastes; cf. Lilja et al. (2011). The life-cycle considerations of products themselves, in terms of their downstream use and consumption, are however outside of the remit of such permitting pressures.

MEf, BAT and environmental management systems

The issue of a possible role for environmental management systems (EMS) in MEf under IPPC/IED legislation is also an interesting subject for investigation. The management of environmental aspects is an important part of a company's activities nowadays due to tightening environmental legislation and customers' and others stakeholders' requirements that attention be paid to environmental effects on an on-going basis. In addition to production-related emission impacts, such as those controlled directly under IED permits, environmental aspects also need to be considered in areas such as product planning and development (in relation to raw materials for instance.)

As with the management of any organisation's day-to-day operations, systematic approaches in the form of environmental management system specifications have been developed to aid the successful corporate management of environmental issues via the organisation, planning, management and review of environmental management aspects. The EMS standards, such as those developed by the International Organization for Standardization (ISO) (e.g. ISO14001) and also an analogous EU scheme - The Eco-Management and Audit Scheme (EMAS - EC 761/2001) (EC 2009d), are now identified in BREF guidance as *voluntary* BAT, as a way to establish environmental protection-related operational guidelines suitable for all levels. In this respect the use of EMS is now widespread in the process industries.

There now also appears to be sufficient legal backing for consideration of regulating MEf specifically in environmental permits in support of the view of Lilja et al. (2012), derived directly from the goal of waste prevention, but also from the criteria for defining BAT under IED (EC 2010b). However, in this regard the linkages between the objective of sustainable use of natural resources, waste legislation and the environmental permitting of industrial production would still need to be made more explicit.

The role that environmental permits could play (e.g. concerning recycling of industrial waste flows) could be significant in this respect due to the relative size of Finnish process industries in relation the country's economy.

By-product assessment

The most important issue associated with the recycling of bulk industrial residues in Finland is still unsolved, namely the creation of an operational framework for converting a waste into a product. According to Sorvari (2008) this requires a detailed description of the practical actions needed and the nomination of an authority responsible for inspecting the conformity of material properties against environmental requirements.

Paper IV reports that based on interview data there seems to be a need for a new operational system to achieve this in Finland. The paper presents a new procedure that could lead to the increased utilisation of bulk industrial residues for major development proposals based on an analogous approach to the well-known and widely applied Environmental Impact Assessment (EIA) procedure derived from the EC EIA Directive (EC 1985). This approach provides an environmental input to the decision making process, where the purpose of the EIA is to focus on the significant environmental effects of a development. At the beginning of the process (i.e. at the EIA Programme stage) there should be an assessment of alternatives to the proposal, where one alternative is the so-called 'zero alternative' (or no action) and a few alternatives should be proposed (i.e. development actions). In a similar approach to this, **Paper IV** proposes a procedure termed a '*by-product assessment procedure' or BPA* where there would be at least three alternatives: 1) straightforward use of residue; 2) use of virgin resources instead, and 3) no alternatives (or the 'zero' alternative). Following an analogous procedure to that of an EIA, such a proposed BPA approach could continue through to impact analysis and then to report and review where the findings are written up in a report which is submitted to the determining authority together with the application for consent for the project; cf. Brady (2005).

After such a procedure the decision maker would have all the information needed to decide whether they had access to, and could use, specified industrial residues or not, and whether it would be reasonable and justifiable from an environmental and economic point of view. For example, the identification of an unacceptable environmental impact may lead to a redesign of the project, or in our case of simply not using an available residue. Also, in this BPA model the public has an opportunity to review the proposal report and comment to the decision-making authority. A practical example of how this could operate in the case of major publicly funded infrastructure projects and the linkage to project acceptability and the issue of land use planning and environmental permits is also outlined in **Figure 21**.

In essence, this would be an approach that places the responsibility for determining whether usable industrial residues for utilisation in construction exist within a given area on the developer. Such a BPA approach deserves more attention and could significantly increase the quantities of residues recycled into beneficial applications, e.g. as an adjunct to WRAP type approaches.

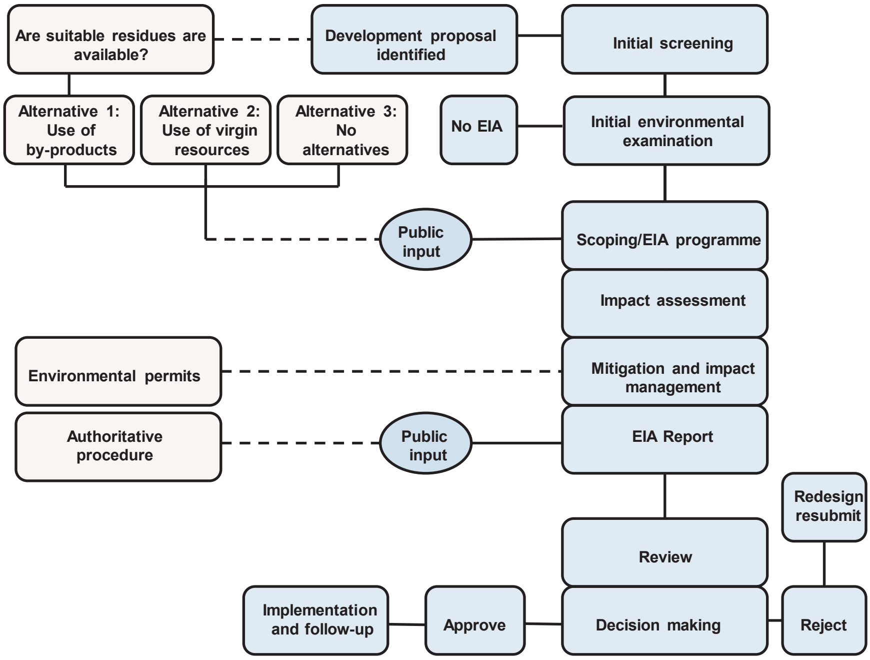

Figure 21 *Proposed EIA-based By-Product Assessment procedure (BPA) for residue utilisation (modified from Paper IV)*

4.2.3 Sustainability management as a driver

That environmental pressures and social awareness are defining features of a changing future economic climate is not in doubt. Adaptation is key here, with sustainable strategically orientated businesses likely to enjoy competitive success, and here the forest industry in particular is in an enviable position, with respect to both its basic raw materials and access to major proportion of its energy being from renewable sources. Businesses have incentives to seek efficiencies, so with a strategic outlook and vision as a destination there are business management tools that can help with the journey by mapping out a route. Here, the development of momentum for effective drivers to establish such business visions for sustainability management will rely on institutional aspects at all levels and identifying unifying issues for industry and public bodies.

Paper VII assessed a range of EU level broad policy and specific legal instruments to determine those with sustainability management implications, particularly in relation to actions concerning material efficiency and the utilisation of production residues. The paper looked at how to bridge the gap between industry initiatives and environmental steering at the EU level, particularly the identification of gaps between industry initiatives and public environmental steering and on suggesting how these gaps could be addressed. The focus here was on the forest products industry. A summary of the potential management implications of the EU's broad policy instruments is summarised in **Tables 4** and **5**.

The main focus areas, key premises and key challenges associated with these instruments are identified. In terms of policy instruments, the results highlight that the broad field of sustainability management covers multiple intertwined issues and areas, and in this respect the findings show the importance of an integrated approach to sustainable industrial development. The firm integration of the policy context at the EU level is clear. However the main findings are that the implications for industry attempting to interpret and respond to these policies is problematic at both the sector and organisational levels.

Table 4 *EU policy instruments - potential sustainability management implications - Paper VII*

EU instrument	Main focus areas and key premises	Challenges
Sustainable development strategy	- Integration of the principle of sustainable development into policy-making - Sustainable natural resources management	- Integration of sustainability principles into strategic management and informed decision-making - Sustainable production patterns - Sustainability management and assessment - Environmental performance of products - Resource-efficient and low carbon solutions
EU Thematic Strategy on the Sustainable Use of Natural Resources	- Sustainable use of natural resources - Life-cycle thinking - Efficient resource use, material efficiency, waste recycling (less to landfills) and more sustainable consumption and production patterns	- Integration of environmental impacts into decision-making and strategic management - Application of life-cycle thinking and criteria (resource-specific) to measure progress towards more sustainable management practices jointly with impact assessments
Thematic Strategy on the Prevention and Recycling of Waste	- Comprehensive approach to waste prevention and recycling covering issues such as the utilisation of waste as a valuable resource to be recycled for further use in manufacturing industry	- Application of life-cycle thinking to waste management - Implementation of minimum standards for recycling activities and recycled materials - Prevention of waste generation and promotion of recycling and waste recovery (avoiding landfilling)
Integrated Industrial Policy (IIP)	- Transition of EU industry to a low carbon and resource-efficient economy - Focus on the whole value and supply chain from access to energy and raw materials to the recycling of materials - Reduction of greenhouse gas emissions and increased resource and energy efficiency - Product policy based on a life cycle perspective	- More material resource and energy efficient production - Increased use of secondary raw materials - Development of new low-carbon production technologies and techniques for energy-intensive material processing industries - Reduction of CO_2 emissions - Strong focus on recycling and raw material substitution - Full life cycle perspective in production planning and product design - Business model sustainability (existential)?
Resource efficiency flagship initiative	- Resource efficiency (sustainable use of limited resources) - New products (fewer inputs) - Low-carbon technologies (fewer emissions) - Waste minimisation	- Incorporation of resource efficiency into decision-making and strategic management - Recycling to: 1) reduce demand for and pressure on primary raw materials, 2) support re-use of valuable materials instead of disposal as waste, and 3) reduce energy consumption and greenhouse gas emissions - Improved product design for decreased raw materials and energy demand and easy recycling
EU raw materials initiative	- Sustainable supply of raw materials - Utilisation of secondary raw materials - Substitution of primary raw materials - Reduced negative environmental impacts	- Incorporation of sustainable use of raw materials into decision-making and strategic management - Resource/energy efficiency and recycling of end-of-life products (life cycle thinking) - Institutional acknowledgement and promotion of status of renewable materials via business incentives?
Integrated Product Policy	- Life cycle thinking - Reduction of the environmental	- Incorporation of life-cycle perspective and sustainable production planning into

(IPP)	impact caused by products through continuous improvement of the environmental performance of products throughout their whole life-cycle - Full stakeholder involvement (whole life cycle of products)	decision-making and strategic management - Development of management approaches for improved environmental performance and minimum environmental impacts of products - Implementation of the full stakeholder involvement during the whole product life cycle

In terms of individual companies in the forest sector, the survey results indicate that the most important stated future goals within forest products industry and individual companies encompass the sustainability of all operations and the improvement of environmental performance and that both stakeholder demands and developments within the regional (EU) and global operational environment has created pushing forces to advance sustainability management. In addition to these broad policy drivers, the demand for enhanced sustainability management is also coming from customers or shareholders creating increased pressure and market demand for the incorporation of sustainability into corporate strategy. These results also indicated that the EU operational environment is both creating new challenges and providing new opportunities, however developments have had implications for the forest products industry and many companies consider it to be difficult to obtain information on the practical implications involved and new opportunities associated with the latest EU and national developments.

Table 5 *EU legal instruments - potential sustainability management implications - Paper VII*

EU instrument	Main focus areas and key premises	Potential challenges
Ecodesign Directive	- Application of a life-cycle perspective with a focus on the main environmental aspects over the life-cycle of products (energy and resource efficiency) - Integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle	- Incorporation of life cycle management into strategic management and decision-making - Continuous improvement of the environmental performance of products throughout their whole life cycles - Improved energy and resource efficiency
Directive on industrial emissions (IED)	- Reduction of industrial emissions - Integrated approach to environmental performance	- Environmental performance of an industrial plant as a whole in environmental permits - More focus on material efficiency (raw materials) and energy efficiency - Integrated approach to 1) pollution prevention and control and 2) emissions, waste management, accident prevention and Best Available Techniques (BAT) - Waste prevention and recycling (in accordance with WFD)
Waste Framework Directive (WFD)	- Waste Hierarchy - 'Recycling society'	- Implementation of the waste hierarchy – i.e. the application of life-cycle thinking and prioritisation of waste prevention, utilisation and recycling/recovery operations over disposal - Implications of the *end-of-waste* (EoW) legislation and criteria for product systems with multiple residue streams - Whether EoW status applies or not
REACH Regulation	- Chemicals safety and related procedures	- Status of 1) highest volume residue streams likely to be utilised as 'raw materials' and 2) low volume, low value residue-based products as 'articles' (each requiring own REACH risk assessment)

The survey results reported in **Paper VII** also indicated that the current status of sustainability, life-cycle and environmental management in respondent companies is mostly influenced by changes in the operational environment and by developments within the industry. In this respect only 25% of companies considered that their management approach was proactive and self-driven. This lack of a strategic approach could be related to the relatively low level of integration of key topics such as resource and material efficiency, life-cycle thinking, low carbon solutions and familiarity with general concepts, especially the sustainable use and management of natural resources. For example, almost half of surveyed companies were familiar with the broad concept of industrial ecology (IE) and activities related to local industrial symbiosis (IS), but many of the companies were still unsure or unaware of IE and IS type concepts in general. However, as de Benedetto and Klemes (2009) recognised, companies are interested in the economic benefits of research results, but often fail to integrate the findings into production and process development or into decision-making and marketing. This means that significant potential is lost when the full market potential of sustainability and environmental management is not duly recognised and/or understood.

The overall findings suggests that sustainability and life-cycle management are not receiving enough management focus at the moment and neither does the forest products industry perceive itself as receiving enough guidance, at either the EU level, or via national steering and through regulatory frameworks and guidance.

An issue highlighted by other researchers in the IS field; cf. Mäkelä (2012), is that without active drivers to encourage risk taking in the pursuit of industrial symbiosis ideas such as those presented here (i.e. institutional encouragement for more research on practical efforts for investigating potential future applications for residue utilisation concepts for example), progress towards inherently more sustainable cyclical resource use models could remain problematic.

In general, the findings support the points made within the sustainability science discourse on the need for more focus on comprehensive and integrative approaches, identification of interconnected elements at all levels, multiple stakeholders and incentives for the implementation of sustainable practices (Kates et al. 2001; Baumgartner 2011).

Forest industry companies in particular operate globally and they need to take into account economic, ecological and social aspects of sustainable development and associated sustainability management. It is therefore worthwhile for them to continue to place more emphasis on the development of sustainability management as an integral part of corporate responsibility in this sector.

4.2.4 Finnish context

The detail of the context relevant to the resource efficiency and waste questions as well as the domestic approaches in the form of policies, plans and legislative aspects designed to implement EU policy and law were discussed in **Papers IV, V** and **VII.** The institutional barriers that have to be addressed and the general drivers that need to be promoted for the development of industrial residue-based utilisations and symbiosis products within the domestic Finnish policy and legal framework implementing EU policy and law are summarised in **Table 6**.

These papers found that, Finland's waste-related regulatory framework does not address the specific legal challenges imposed by potential symbiosis products composed of residual materials (product systems with multiple residue streams used as raw materials). Furthermore, the utilisation of materials or substances defined as waste in symbiosis products and consideration of the application of product-based legislation and associated standards to these products will require further legislative development. The new waste regime does allow recycling and reuse of residual materials, however involved operators will need more information on the potential EoW status of both combined residues and any resulting symbiosis products in order to make progress on increased residue utilisation.

Table 6 *Implications for the development of symbiosis products - summary of Finnish instruments - Paper IV*

Instrument	Identified potential institutional barriers	Suggestions on how to bridge the specific institutional barrier
National Waste Plan	Lack of guidance on: 1) material efficiency and recycling encompassing new quality and environmental compliance criteria for certain recycled materials (e.g. permit or notification), 2) the use of waste-based fertiliser products and 3) recycling of industrial waste flows through permit conditions and guidelines for individual waste categories	Establishment of clear institutional status for: 1) management approaches and practical measures to promote material efficiency, recycling and waste prevention, 2) duties and knowledge requirement of operators, and 3) best environmental practices and related standards (e.g. clear procedures and requirements for environmental permits)
Waste Act (646/2011)	Lack of practical guidance on: 1) the implementation of the Waste Hierarchy, 2) responsibility for waste management and associated costs, 3) efficient use of raw materials, 4) use of waste, or raw materials made from waste, as raw material and 5) awareness of waste origin, quantity, and quality (manufacturers)	New institutions for the practical enforcement and implementation of: 1) the Waste Hierarchy, 2) efficient use of raw materials and use of wastes or raw materials based on waste, 3) sustainable use of natural resources taking into account full life cycle impacts of products and waste, and 4) management of waste origin, quantity and quality (manufacturers)
Waste Tax Act (2010/1126)	Clarification of the institutional status of: 1) waste recovery/utilisation as a separate activity from landfilling under the waste tax, and 2) taxed waste types - are all waste flows covered?	Enabling institutional environment for economically viable industrial waste recovery/utilisation operations (e.g. design of effective and coherent incentives)
Environmental Protection Act (86/2000)	No information on: 1) appropriate approaches to sustainable use of natural resources in the context of waste management and recycling (focus on waste prevention), 2) best environmental practices concerning waste recovery, and 3) specific knowledge requirement of operators	Institutional development for practical and locally orientated approach to: 1) waste recovery, 2) duty of operators, 3) environmental permits (precedence to waste recovery and reduction of waste generation), and 4) knowledge requirement of operators
Fertiliser Product Act (539/2006)	No information on the potential status of symbiosis products (based on multiple residue streams) as safe fertiliser products (good quality and suitable for plant production)	Clear institutional status of symbiosis products (based on multiple residue streams) as safe fertiliser products covering, e.g. uniform quality, suitability for their purpose of use, safety of the raw materials and fulfilment of the quality requirements
Chemical Act (744/1989)	No information on the general duties of manufacturers of symbiosis products (based on multiple residue streams) covering awareness of physical and chemical properties of the chemical and of its health and environmental impacts	Clear institutional status of the general duties of manufacturers of symbiosis products (based on multiple residue streams) covering awareness of physical and chemical properties of the chemical and of its health and environmental impacts

Finland's MOTIVA initiative

Enabling others to recover as much value as possible from waste, as a material resource or as energy, and to help keep resources moving round the economy is key to any resource efficiency approach, with savings translating into less demand for scarce natural resources. The example of the UK WRAP approach to the problem is useful for informing future Finnish approaches to this issue and a possible future role for MOTIVA (see Section 3.9.4). However, where these approaches differ most is in the strong focus on markets adopted by the UK's WRAP, where the key to building resource recovery networks is seen to be firmly in the ability to create and strengthen market confidence in residue quality standards and build networks to support steady utilisation of EoW residue streams etc. The clearest example of the success of this approach is seen in the UK *waste protocols* system, which supports that country's EoW process.

Business culture and institutions

The waste management approaches of the process industry companies are production-orientated and technology driven and naturally they are used to dealing with only their own business and managing their own by-products and wastes residues. With respect to process industry culture, at present the existence of an inter-industry field or discussion in Finland seems to be led mainly by academic researchers, who have pointed out that quite apart from the opportunities within particular process industries there are also inter-industry possibilities with respect to modification and amalgamation of solid residues to create symbiosis products; cf. Heino et al. (2008), Mäkelä et al. (2010; 2011), Mäkelä (2012) and Husgafvel et al. (2012), Wierink et al. (2010).

The sort of cooperation that is needed between companies in different process industries for more effective use of residual material is therefore a new proposition in industrial activity. In this respect the interplay between industrial symbiosis and environmental regulation is a highly dynamic system (Salmi et al. 2011), with outcomes that are often difficult to predict. However, intervention through the setting up of institutions to specifically support continued research and cooperation in this area would help create the right climate for seeking further benefits.

Papers II, III and IV explored how this issue needs to be addressed through initiatives to actively set up foci for exchange of ideas on symbiosis, material characteristics and areas where the development of residue-based material performance criteria can support EoW criteria development in particular circumstances and production and consumption industry groupings. Here, the example of the UK's WRAP approach to institutional arrangements to align real residue material specific arrangements with market incentives for residue-based raw materials quality protocols development is instructive. Further initiatives directed at research and support of wider industrial ecology ideas could also support lower level materials efficiency efforts in this respect. Indeed, **Paper IV** identifies another existing example in the form of the UK's National Industrial Symbiosis Programme (NISP) as being useful in this regard, a role for which Finnish institutional approaches, e.g. such as that of MOTIVA, could also be used (NISP 2013). Here, the UK's additional initiative offers symbiosis network advice that aims to provide more holistic support to bring together traditionally separate industries and organisations from all business sectors with the aim of improving inter-industry resource efficiency and sustainability (NISP 2013). This is a linkage that is specifically absent in Finland on a formal basis and often only occurs via academic intermediaries as highlighted by our Finnish case study (**Figure 22**).

In terms of the organisational aspects involved in symbiotic relationships we must not underestimate the differences in the cultures of the companies who might supply residues or form a network. Many of the industrial companies have an engineering culture now in transition to a more customer focussed culture. The similar culture of two main hubs such as the metals and forest products sectors, coming from a shared industrial history might be the strongest component in forming industrial symbiosis relationships or wider ecological networks. Due to history, long tradition and similar educational background in particular industries some co-operation within an industrial sector is possible but without some sort of active external encouragement and coordination, almost none between sectors is likely to occur.

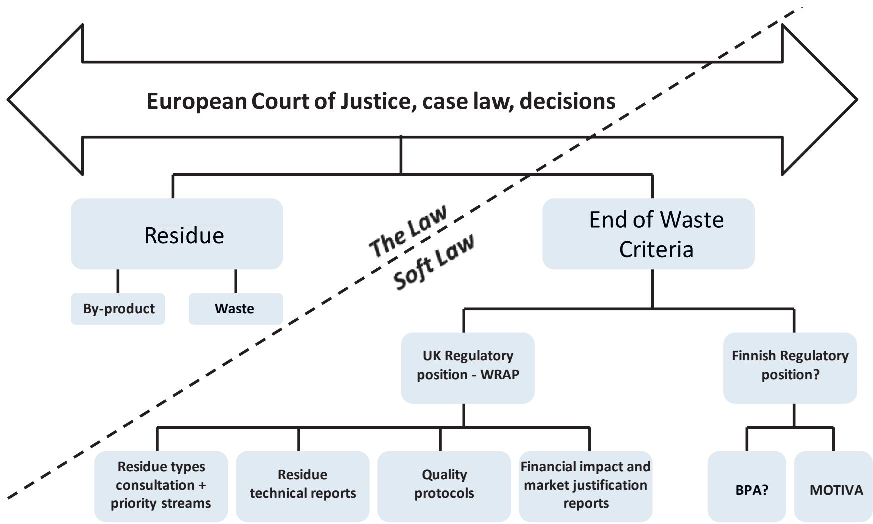

Figure 22 *Quality Protocols, end-of-waste (EoW) and markets - UK and Finnish Comparison (modified from Paper IV)*

The utilisation of materials or substances defined as waste in symbiosis products and consideration of the application of product-based legislation and associated standards to these products will require further legislative development. The new waste regime allows recycling and reuse of residual materials, but involved operators will most likely need more information on the legal status of their residues and by-products to augment any other institutional arrangements. These institutional aspects need to be strengthened and supported.

4.3 Environmental performance of products - case studies

In **Paper VI** both a life cycle assessment (LCA) approach and exergy analysis were applied to the development of these residue-based symbiosis product concepts with the aim of comparing their environmental performance in terms of Global Warming Potential (GWP) with similar products based on virgin primary raw materials and on the alternative treatment of these residues as wastes. **Paper V** investigated the performance of similar residue-based soil amelioration pellet formulation concepts in terms of their physicochemical properties, total element concentrations and their likely environmental impact in terms of mobility and the potential bioavailability of chosen heavy metals.

4.3.1 Sustainability performance

The main goal of the assessment made in **Paper VI** was to determine the GWP associated with the manufacturing of potential symbiosis products based on multi-stream industrial residues. GWP was used as a measure of environmental burden expressed as carbon dioxide equivalents (CO_2-Equiv.) which is a unit for total greenhouse gas emissions and related climate impacts. The choice of only GWP as a measure of environmental burden means that the focus was on climate change related air emissions in particular. This means that the results of the study did not address other impact categories such as, for example, resource use/depletion or land/water environmental quality impacts.

The scope and system boundaries of this study were based on the goal statements and related choices of reference processes and functional units. For the potential symbiosis products, the scope of the GWP assessment covered the transport of secondary raw materials and the actual manufacturing processes. The primary processes (the sources of the residues) were left outside the system boundary and allocation was avoided through study of separate sub-processes which utilised recycled/recovered wastes as burden-free secondary raw materials. Thus the GWP results only describe these sub-processes as examples of potential utilisation of multi-stream residues in these hypothetical cases. The scope for the primary product examples was from cradle-to-gate i.e. the studied system encompassed raw materials extraction, transport and the manufacturing processes.

The software used in the assessment (GaBi 4.4) (PE International 2006) calculates the potential environmental impacts and other important quantities of a product system based on process plans. Further, the GaBi LCA software used has been developed in accordance with the requirements of environmental management standards concerning the principles and framework for an LCA (ISO 14040) and the requirements and guidelines for LCA (ISO 14044) and is compatible with the International Reference Life Cycle Data System (ILCD 2011). The software also utilises both the European Reference Life Cycle Database (ELCD) and the CML (2001) impact assessment method collection which categorizes Life Cycle Inventory results according to themes (CML 2001; ELCD 2010; GaBi 2010; PE International 2010). The process diagrams (GaBi plans) of the manufacturing of potential secondary products are presented in Annexes 1 to 4 to **Paper VI**.

The results of studies undertaken in **Paper VI** showed that there is potential for the improvement of process industry sustainability through further research into the replacement of similar commercial products delivering similar functions to those based on virgin primary raw materials and avoidance of the treatment of residues via waste disposal. The results of the GWP assessment and exergy analysis of the hypothetical case studies indicate that there are potential environmental benefits associated with the utilisation of multi-stream industrial residues as raw materials for potential symbiosis products in terms of their relatively low GWP figures and high level of exergy efficiency provided that the associated manufacturing processes would be not energy-intensive and very limited or no primary raw materials would be used.

The functional unit used was 1000 kg of finished end product in both symbiosis product cases and examples of products similar to ones based on primary raw materials, except for the example of slag compartment construction in which the unit was 1000 kg of disposed bottom ash, and for the example of landfilling of green liquor dregs in which the unit was 1000 kg of landfilled dregs. The choice of the functional unit(s) (in its role to ease comparison of outcomes) was chosen on the basis that it was on the same scale as the studied substitutions (i.e. land amelioration products are marketed and sold in

€/tonne and applied at rates expressed as t/Ha etc.) Similarly, bulk users of OPC relate to tonne quantities in marketing and usage, and landfill functions are sold at per tonne prices etc.

The case studies indicated that the manufacturing of such symbiosis products would cause relatively low environmental burdens in terms of GWP where the residues are classified as burden-free secondary materials (**Table 7**). It was assumed in these hypothetical case studies that these material flows exist and that they are currently considered as waste with no recycling options. The results only indicate the potential benefits of taking the product-oriented approach (in terms of GWP and overall resource efficiency aspects) and they do not make any suggestions relating to broader industry impacts or total net emissions of some industrial systems whether they stand alone or are joined within specific local IE/IS setting. Recycling of process industry residues into secondary raw materials for potential symbiosis products can especially reduce the environmental burden associated with: 1) the manufacturing of equivalent products based on primary raw materials (replaced products and production) and 2) landfilling of industrial residues and related construction. These environmental benefits are realised through the substitution of other products based on primary raw materials as well as through avoided environmental burdens associated with landfilling and its related construction activities. However, the assessment of environmental impacts gave rather predictable results in comparison between the different options on an exergy analysis basis (**Paper VI**), i.e. exergy analysis reveals that the replacement of OPC clinker, where applicable, will definitely provide the greatest opportunities on environmental burden reduction considering the processes studied here (i.e. the simple result of avoided calcination and combustion emissions from OPC manufacture through their substitution by residues). Although not quantified in **Paper VI** the avoidance of virgin material costs and also waste management costs would likely be highly favourable to further research into the financial viability of specific symbiosis approaches, especially for pellet and mine filler replacement products.

***Table** 7 LCA study results (modified from Paper VI)*

	Product cases	**Global Warming Potential (kg, CO_2-Equivalent)**	**CO_2-emissions (kg)**
Secondary products	Soil amelioration pellet	1.60	1.60
	Low competence concrete	2.00	1.90
	Mine filler	0.13	0.12
Primary products	Limestone (agricultural lime flour)	12.2	11.4
	NPK 15-15-15 fertiliser	1,496.7	845.2
	Concrete element	123.8	118.8
	Ordinary Portland cement (OPC)	899.2	885.1
	OPC based - Mine filler	1.5	1.4
	Slag compartment[a] (bottom ash)	5.58 per 1000 kg ash 3,141,303 total	5 kg per 1000 kg ash 2,816,680 total
	Landfill (green liquor dregs)	334.0	320.7

a 375000 m^3 landfill compartment

This approach to residue utilisation could be a more sustainable option for industrial processes therefore, since the environmental performance (e.g. in terms of GWP) of these symbiosis products is low when compared to the performance of similar commercial products based on virgin primary raw materials and the treatment of residues as waste (i.e. the current situation/management approach). However, widescale cement substitution opportunities are limited, due to the relatively small quantities of suitable residues available from the pulp and paper industry compared to the magnitude of the throughput of the limestone-based cement industry. The magnitude of slag production from the steel industry does however offer significantly greater potential in the case of slag replacement in cement manufacture.

4.3.2 Environmental suitability

In **Paper V** the focus was on the investigation of certain parameters of industrial residues and formulations manufactured from them that may have beneficial agricultural, as well as possible adverse environmental impacts upon utilisation, such as trace element content and their respective availability. Chemical analysis of candidate soil amendment formulations included essential physicochemical characteristics, easily available plant nutrient concentrations and trace element availability. The characteristics of the formulations were also further examined from the perspective of the ecological criteria for the awarding of the EC eco-label for soil improvers (EC 2006b) and limit values for generic types of fertilisers in use in Finland (Ministry of Agriculture and Forestry Finland 2011).

The main findings were that the industrial residue-based soil amendment formulation made from steel industry desulphurisation slag and fibre industry fly ash, paper mill sludge and lime waste shows promise. In the replacement of commercial liming products the formulation's performance as a soil amendment would be equivalent to normal commercial ground limestone products, indicating a good capacity of such a material to neutralise soil acidity.

Concentrations of easily available plant nutrients (Ca, Mg, K and Mn) in the soil amendment concept were higher than in organic and mineral soils normally found in the Ostrobothnia region, however elevated concentrations of non-beneficial Na and S were found which was unsurprising given the originating process chemistries.

Trace element availability is of course more critical in relation to heavy metals. the pseudo-total[64] concentrations of As, Hg, Cd, Cr, Cu, Mo, Ni, Pb, and Zn were all lower than the limit values for awarding the EC eco-label for soil improvers (EC 2006b). Additionally, the pseudo-total concentrations of As, Hg, Cd, Cr, Cu, Ni, Pb, and Zn were also lower than the Finnish statutory limit values for both agricultural and forest fertilisers (Ministry of Agriculture and Forestry Finland 2011). However, in the case of the EC eco-label limit values for soil improvers the precision of the analysis proved insufficient for the determination of Se to the required accuracy and analysis of F was not performed (**Table 8**).

As shown in **Figure 23**, As, Cr, Cu, Mo, and Pb availability was mostly associated with Fraction 4, generally referred to as the residual fraction generally only dissolvable by digestion with strong acids. As a method for chemical speciation, sequential extraction procedures apply each successive reagent in order of increasing reactivity which thus correspond to association forms of decreased mobility. In other words leaching is representative of element activity in the environment with each successive extractant being more aggressive than the previous one. Such extraction studies are often applied to assess the worst case environmental scenario in which all elements become soluble

[64] *Pseudo-total* - the use of a less aggressive digestion method designed to indicate bioavailabilty which does not completely degrade sample matrix (i.e. HCl and HNO_3 instead of HF, HCl and HNO_3).

and mobile. With Ba and V, (which are not included in the limit values for awarding the EC eco-label for soil improvers) mobility was more pronounced in Fractions 1 and 2.

Table 8 *Pseudo-total concentrations (mg kg^{-1} d.w.)*[65] *of the soil amendment sample, Finnish statutory limits and background concentrations for uncontaminated fine till (modified from Paper V)*

Element	Pseudo-total (mgkg^{-1}, d.w.)	Recovery[a] (%)	Limit A[b] (mgkg^{-1}, d.w.)	Limit B[c] (mgkg^{-1}, d.w.)	Soil background[d]
As	3.8	105.8	25	40	<0.3-20
Hg	0.049	[e]	1.0	1.0	
B	15	[f]			
Ba	280	89.3			400-900
Be	<1	[e]			
Ca	371,000	[f]			
Cd	0.83	108.4	1.5	25	
Co	2.8	96.4			<3-30
Cr	82	96.8	300	300	<30-300
Cu	12.5	99.2	600	700	10-70
K	899	[f]			
Mg	8640	[f]			
Mo	1.4	89.6			<0.5->2
Na	6850	[f]			
Ni	17	92.9	100	150	10-100
P	5520	[f]			
Pb	8.2	102.4	100	150	0.1-20
S	4570	[f]			
Sb	<4	[e]			0.1-0.9
Se	<4	[e]			
V	220	91.4			30-180
Zn	41	99.5	1500	4500	30-400

a Recovery calculated as (∑(fractions 1–4)/pseudo-total concentration) × 100%
b Agricultural use limit Finland (Ministry of Agriculture and Forestry Finland 2011)
c Forestry use limit Finland (Ministry of Agriculture and Forestry Finland 2011)
d Finnish uncontaminated fine till soil (Sorvari 2003)
e Below quantification limit
f Not included in sequential extraction procedure

Barium also attested to notable recovery especially in Fraction 1 (**Figure 23**), which is the most labile[66] fraction of the procedure. The pseudo-total concentration of Ba was reported as rather low and recovery was dominated by Fraction 3. However since 31% of the respective pseudo-total concentration was in Fraction 1 this suggested possible Ba phytoavailability and plant contamination in the case of use as an agricultural or forest soil amendment. This is outside the normal range in most plants (2 to 13 mg kg^{-1}) and concentrations of 200 mg kg^{-1} have been found to be moderately toxic.

Vanadium was mainly associated with Fraction 4, but was also recovered in Fraction 2 (26.4 mg kg^{-1}, d.w., 12% of the respective pseudo-total concentration) and in Fraction 3 (54.4 mg kg^{-1}, d.w., 25% of the respective pseudo-total concentration). Although V was not recovered in Fraction 1, availability associated with Fraction 2 could occur by changes in the oxidation or reduction potential of a natural medium (Manskinen et al.

[65] USEPA 3051A
[66] *Labile* - readily available.

2011). In concentrations lower than 2 mg kg^{-1} V could have a positive effect in plant synthesis but higher concentrations could cause chlorosis and limit growth.

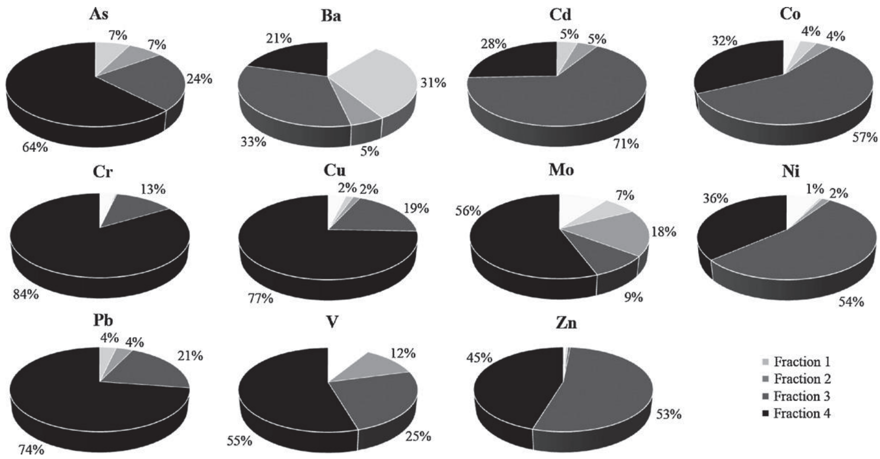

Figure 23 *Individual fraction recoveries (%) of trace elements As, Ba, Cd, Co, Cr, Cu, Mo, Ni, Pb, V, and Zn in fractions 1-4 during the modified BCR[67] approach - Paper V*

Thus, in addition to Ba, possible V availability to plants requires further research on potential plant utilisation. Vanadium was also the only trace element with a pseudo-total concentration that exceeded available Finnish background values for soils (i.e. 30 - 180 mg kg^{-1}) of uncontaminated fine till provided by Sorvari (2003).

Only Ba and V, [which are not included in either the revised eco-ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to soil improvers (EC 2006b) or the Finnish legislation of fertiliser products Finland (Ministry of Agriculture and Forestry Finland 2010)] indicated potential availability under natural conditions. The results therefore demonstrated that the proposed soil amendment concept would probably fulfil some of the essential elements for qualification in terms of lawful use.

Variability in residue quality

Fluctuations in input material quality are difficult to address since it involves plant specific aspects and the uncertainty of environmental analysis of residuals depends on the effects of process conditions and stability on the concentration of potential contaminants. Further effects of process variations on potential trace element solubility was not performed as it would have required a lot more resources. However this issue has been subsequently identified and published for two of the residues. In Mäkela et al. (2013) the published work covered only one residue from the steel industry (ladle slag), accordingly, the variation in process conditions had a potentially considerable effect on the (pseudo-total) concentrations of e.g. Cr based on a six-week sampling period. According to Husgafvel et al. (2013), the suitability of the potential soil amelioration pellet concept as a forest fertilizer product may also be limited by the concentration of As in the fly ash component for a specific installation, but that the determination of this requires more analyses. The variation between residues from different installations is therefore in need of more research.

[67] *BCR* - Community Bureau of Reference

Issues with concentration limits that are set by regulatory authorities is also highlighted by the results from this more sophisticated BCR type approach - where the use of total concentrations in limit values describing potential environmental impacts is shown to be insufficient in describing the real mobilisation capacities and behaviours of the target species under extreme pseudo-environmental conditions.

4.4 The value of ecological thinking

The impossibility of unlimited physical growth holds even though growth might be efficient (Welford 1998). Nevertheless, eco-efficiency has become the main vehicle for addressing industrial sustainability and as such its conventional neoclassical economics' way of thinking is becoming the dominating vision and overall objective of various environmental and sustainability policies and management strategies worldwide (Hukkinen 2003). However, the effect of reduced impacts gained from eco-efficiency gains alone will ultimately be overtaken by absolute growth (through the effect of rebound) without addressing the implications of the continued economic growth assumption or axiom. Some claim that key priorities here should include the establishment of resource caps (i.e. limits to utilisation) to reduce the unsustainable burden on our planet's ecosystem caused by inefficient use of natural resources (Hoffrén and Korhonen 2007). Such ideas are explained as ecological caps that converge to sustainable levels (Jackson 2009). Ehrenfeld (2005) has also observed that eco-efficiency results in a host of technological fixes that leave untouched the underlying causes of environmental problems and that eco-efficiency gains so far are too small to offset growing threats (i.e. that reducing 'unsustainability' does not produce sustainability.) The fact that the establishment of an international consensus on any such limits in a dynamic, evolving system would be difficult to obtain is pointed out by Costanza (1999) and (Hoffrén and Korhonen 2007).

The basic premise of much of the general literature focussed on industrial sustainability and specific residue utilisation studies is that improving the resource efficiency of production systems is a goal that supports the process of sustainable development. The papers in this dissertation **Papers I-VII** all present the industrial symbiosis (IS) approach and life cycle thinking as useful methods for approaching specific process-related residue stream efficiency improvements as a valuable near-term objective. However, the value of ecological thinking extends into a broader paradigm that defocuses away from IS to consider the possibilities of more holistic approaches to sustainability. This part of the discussion expands on the subject of IS within the broader field of industrial ecology (IE) and examines the application of these metaphors in our economy's industry.

The complex nature of systems becomes evident when the dynamic interactions between drivers at different levels are considered. Natural resource reserves have until recently been able to sustain the ways we achieve our economic growth but there are valuable lessons to be learned from the study of ecosystems as sustainable communities of plants, animals and microorganisms. The interdependence found in ecological systems offers ideas for thinking about the organisation of a more sustainable human society. As in natural ecosystems, our own human ecosystem is a complex arrangement of interdependent elements at all levels with often a non-linear cyclic coupling. Similar reasoning is currently employed by horticultural approaches such as the use of permaculture[68] ideas where focus on food production from land is a keystone linking other domains that require transformation to create sustainable forms of human culture.

[68] *Permaculture* - the development of sustainable human settlements and self-maintained agricultural systems modelled from natural ecosystems.

4.4.1 Life-cycle thinking

Industrial systems can be studied at different spatial and temporal scales as previously shown in **Figure 10**. In terms of our society's coupling with the environment there are issues with the difference in frequency and the time lag between cause and effect in different ecological systems. In other words the reaction and relaxation times of our economic, technological, institutional and social meta-systems with those of natural systems are different and this difference in system frequency and also issues of relative system size can damage interaction and outcomes of potentially common interest.

Industrial ecological systems are potentially large systems where conglomerates of players interact. These players are industries, policymakers, consumers, and individuals, who each have different interests that are attuned to different timescales. The reaction times of different parts of the system may be very different and might conflict. Also, although companies might be able to obtain benefits from symbiotic/ecological networks there are also business risks associated with deep integration within the fabric of a local industrial symbiosis or wider regional ecosystem. The operational life-cycle of an anchor tenant industrial process such as a power station [see the example of Kalundborg (Grann 1997)] needs to be considered by potential symbiosis partners if they are to rely on exchanges of energy and materials. If business investment confidence is low then firms are also less likely to seek opportunities and exposure to other organisations and partnership approaches become more difficult in marginally profitable areas. Seeking such partnerships during difficult economic climates may also introduce business risks related to continuity of supply of materials etc.

The overarching timescales that cannot be changed and can only be adapted to are also important, for example those consisting of timescales dictated by the interaction between natural ecological systems and an industrial ecology. Advances in technology can optimise and shorten industrial ecology's frequency or the operational life of processes, but natural relaxation and response times cannot be changed within a time frame that is meaningful to industrial and societal development. For example, short term investment horizons or economic thinking (5 to 10 years) as well as development and implementation of policy (5 to 15 years) and even capital investment periods in process industries (25 years or more) are too short for broader social and economic systems let alone natural environmental systems to interact. There are also issues with the difference in time lag between different systems (the reaction and relaxation times of economic, technological, social, and natural systems are different) they are not in sync and there are highly latent impacts.

It is also important to acknowledge that temporal frameworks are physically or ecologically imposed or culturally constructed and these frequencies are at odds with the cycles of international finance and investment. Similarly, waste arises from the design of non-embedded products (artefacts) which are outside of biological cycles. Such persistent artefacts can therefore largely be equated with inorganic waste streams. The consumption of products conceived and designed solely on their functional and utility merits are detemporalised and decontextualised, in other words there is not an extension of time dimension into planning for whole product life history and impacts upstream and downstream (including their use and disposal or reutilisation.) In this way, the designed obsolescence of consumerism and positivistic science are poorly suited to engaging with natural time frames; cf. Adam (1995). Inorganic artefacts are not yet therefore designed to be connected or embedded in natural cycles, to ecological organic flows, they are externalised, abstracted and bounded.

These differences in system frequencies, the detemporalisation and decontextualisation of products hamper interaction and outcomes that could be of common interest to both society and the environment.

Looking at IE and IS we have structural aspects like systems for using, labour, materials, machines but weak process aspects like policy, goals and cognitive aspects to allow adaptive changes in behaviour. There is therefore very weak or no system steering due to inadequate feedback between structure and process. Our systems have no autonomy and cognition but that which we give to them through our agency and our own human policy and signals are complex and confused. In this sense economics is an unreliable indicator for coupling with our industry as is the environment itself (e.g. an extreme example being the length of climate change response times). The result is that human technology is not shaped by environmental response, either directly or reliably (e.g. delayed environmental responses and lack of adequate and timely economic signals.) In this respect human systems that are more attuned to negative feedback through environmental signals would be a step towards guarding against over-exploitation of resources. A complex adaptive model of an industrial ecology (a flexible and adaptive system) could therefore only arise from its communication with the environment outside its boundaries as some form of situated strong structural coupling via suitable feedback signals. The problem thus far has simply been that industrial societies have been isolated from their environment (as far as structural coupling is concerned) by access to recently cheap fossil fuel energy and its application to the creation of a meta-environment.

Our society's assertion of a linear causal chain or cascade of energy and information in our industry means that there is limited feedback to inform by-product or waste characteristics that could be of use further down chain. Our linear chains are simply too simplistic in this sense. In summary our industrial system determines behaviour top down and there are no emergent attributes.

4.4.2 Ecology and symbiosis metaphors

In **Papers I-VII** both the IS and IE ecological metaphors are used to illuminate possibilities that exists for improving the sustainability of industrial processes. In order to discuss the use of these industry and ecology metaphors in the sustainability discourse it is useful to take an overview of the use of metaphor and its role in general.

Most human thought is metaphorical. Metaphor is language about language, a conceptual transplant (Reddy 1978). According to Lakoff and Johnson (1980), the metaphors we live by allow us to understand one domain of experience in terms of another. In other words they act as non-verbal dynamic images that induce in us a non-linear understanding of systems and their principles - they help us grasp processually and holistically how things work (Adam 1995). The special power of metaphors stems from the fact that they often cross the borders between the intuitive and the formal (Sfard 1997). However, Sfard (1997) further points out that to embrace a whole issue at a glance (using metaphor), one has to reach the most fundamental, primary levels of our thinking and bring into the open the tacit assumptions and beliefs that guide us. Metaphors cease to work however once naturalised, when we no longer recognise them as metaphors. In other words, by virtue of their use, metaphors are concepts in the making; concepts are therefore metaphors that we no longer recognise as metaphors.

According to Rorty (1991), in choosing a metaphor to use, it must fulfil necessary conditions to rank as a candidate, and resulting theories must be convincing and coherent, where 'convincing' includes a belief in the usefulness of the theories and an expectation that they will lead to an inter-subjective agreement and be a potent sense-making tool by being an effective producer of new insights. Aristotle: ‘Metaphors, like epithets, must be fitting, which means they must fairly correspond to the thing signified…’ (Barnes 1984). Being aware of the essentially figurative nature of our sense-making activities, we may sometimes go so far as to merge seemingly conflicting metaphors like these within one theoretical framework. In this sense the industrial ecology and industrial symbiosis metaphors appear at odds, and this is now discussed further in order to determine the usefulness and limitations of these metaphors to the issue of industrial production and sustainability.

4.4.3 Ontological Frames

Paradigmatic issues and ontological aspects that could be drivers for changes in our design approaches in future, such as changing approaches and addressing barriers to change in integrated technological and social systems to address environmental sustainability, need to be discussed to understand the historical metaphors that drive our current thinking.

Science and engineering exists in the language it uses. We create a culture, create our world through communication and shared common meaning of rules, values and beliefs. The philosophical basis underpinning our anthropocentrism and culture of individualism and reductionism is claimed to be one of the roots of our currently unsustainable societies (Ehrenfeld 2008). Western culture’s Cartesian[69] thinking, regarding an assumed division between man and nature, developed out of the Enlightenment and was the basis for positivistic[70] science that delivered a utilitarian industrial legacy born out of the subsequent Industrial Revolution. Additionally, Baconian[71] progressive teleology[72] also makes us always look to technological solutions or rely on technological optimism as a means of addressing problems (Costanza 1999). This confirms our Cartesian outlook as one of being outside nature and nature as a consumable resource. Such ‘technological optimism’ concerning the achievement of sustainability solutions through technological innovation, is thus the prevailing scientific culture that is cautious towards making progress in the direction of more holistic approaches to enquiry. Present approaches have been likened to a modernist technocratic approach to the environment that suggests that there is a techno-institutional fix for present problems (Bluhdorn 2000).

Paradigms and intervention

Writers such as Meadows (2008) have described paradigms as the mind-set out of which a system (its goals, structure, rules, delays and parameters) arises. It is our society’s overarching unstated assumptions that constitute its paradigms, representing our deepest set of beliefs about how the world works. These are often unstated because they are fully accepted, for example the notion that exponential growth is good and even possible inside finite systems. It is these shared social agreements about the nature of reality that provide system goals, information flows, feedbacks and stocks, and are the source of our paradigms. Intervention in systems at the paradigm level can totally transform systems and paradigmatic change can be rapid. There are also paradigms within scientific fields, for example in terms of the limits to the industrial ecology metaphor, its expansion into the policy arena and the normative considerations that arise

[69] *Cartesian* - that complex systems can be reductively explained.
[70] *Positivism* - empirical data as the exclusive source of all authoritative knowledge, environment viewed as other or external to man as direct result of positivistic thinking.
[71] *Baconian* - scientific substitute of the empirical method over systems of pre-Enlightenment thought.
[72] *Teleology* - attempts to explain natural phenomena in terms of design, i.e. that design and purpose analogous to that found in human actions are also inherent in the rest of nature.

over integration of social, political, organisational and cultural factors. In other words, in this respect industrial ecology is subject to mediation via discourse that can result in substantive 'revolutions' in the content and boundaries of the discipline itself as first described by Kuhn (1962). What role can industrial symbiosis play within the field of industrial ecology in this discourse?

4.4.4 Problems with metaphors

All of society's concepts and beliefs have their roots in a limited number of fundamental ideas that cross-disciplinary boundaries and are carried from one domain to another by the language we use (Sfard 1997). The use of different metaphors leads to different ways of thinking because they keep our imagination within the confines of our former experience and conceptions where old foundational assumptions and deeply rooted beliefs (being tacit) prove particularly inert and therefore travel from one domain to another practically unnoticed. Such uncontrolled migration of *metaphorical entailments* is not always to the benefit of new theories since this may bar fresh insights and perpetuate beliefs and values that have never been submitted to critical examination (Sfard 1997). This is also highlighted by Wells (2006) who claims that the metaphorical entailments of IE and IS (such as those of scientific rationalism) that embed these ideas in the Cartesian-Newtonian world view, promote reductionist and narrow conceptualisations inadequate to the task of resolving the complex inter-related challenges of sustainability. In this sense this highlights the *irony of modernity* as the formulation of the environment as 'other' and external to man as a direct result of positivistic thinking or praxis[73].

Do such entailments travel across in the IS to IE to Sustainable Development fields? Can IS be seen as engineering, IE as science, and sustainable development (SD) as mainly social sciences *in extremis*? What are their entailments? In terms of an example of more specific entailments, Hermansen (2006) suggest that the legitimacy and validity earned by the older discipline of biological *ecology* to a certain extent transferred over to industrial *ecology* as a positive emotional resonance attached to the word 'ecology'. Other writers such as Salmi and Toppinen (2007) also argue the implications of a metaphor, such as industrial ecology, are also a result of contextual determinants not less the metaphor itself, where the same figurative idea may engender several greatly varying conceptual frameworks. This was demonstrated by Salmi (2008) in relation to *complex utilisation* as a Russian interpretation that antedates and closely resembles industrial ecology but was not driven by environmental sustainability but rather resource security concerns of the former USSR from the 1930s onwards.

The dictionary definition of *symbiosis* – 'The close association between two or more organisms of different species, often but not necessarily benefiting each member' – seems to have positive connotations in general, but this is not necessarily so, since only one of the four types of symbiotic relationship could be said to be acceptable to all parties. For example, symbiosis covers: 1) the living together of two dissimilar organisms can be beneficial to one without effect on the other (commensalism), 2) an arrangement that is beneficial to one and detrimental to the other (parasitism), 3) one that is detrimental to the first without any effect on the other (amensalism) or 4) one that is detrimental to both (synnecrosis). Despite this, the word *symbiosis* has an overwhelmingly positive connotation due to its entailments derived from its *ecology* background, with the word ecology's entailments in turn having been identified from its origin in the biological sciences (Hermansen 2006).

[73] *Praxis* - the unification of thought and practice.

The increasing frequency in use of the term *ecology* (and the entailments implied therein) has also been noticeable in many other fields, from the biological and scientific to its more recent use for economic and resource management issues, for example the use of such terms in reports such as the Millennium Ecosystems Assessment 2005 (UNEP 2005) and also anecdotally the use of such terms as *investment ecology, business ecology* and *product ecology* etc.

In terms of normative entailments, Hermansen (2006) further points out that we are appealing to technology to help solve problems related to the ecological crisis and that concepts such as cleaner production (CP) represents one such effort, through reducing pollution and increasing energy efficiency, but that IE aims for a more ambitious goal that sees consumption and production as a whole and attempts to balance industrial production with ecological capacity. In other words these wider aims relate not just to individual technologies and solutions but a wider new industrial system or socio-technological society with responsibility for sustainable management of ecological resources. In this view, the implication that the social and normative perspective is much more integrated is indicated by the use of the word 'ecology' (Hermansen 2006).

In general IE has been criticised for having made only a limited contribution to the achievement of a sustainable future (Wells and Darby 2006). This charge relates to it only appealing to the comparative analysis of products and processes (eco-industrial parks and limited industrial symbioses for example.) In other words use of the metaphor as a methodological tool has been predominantly at the IS end of the scale rather than one for societal or economic transformation (which is of course an altogether different cultural discourse or project with inherently normative and therefore intensely political dimensions). The IE field has also been more adept at closing materials cycles at the IS end of the spectrum than promoting a fundamental paradigm shift in industry-ecology relations, and in part this is due to the narrowness of the metaphor and the way it has been used on a small-scale and parochial in practice. Evidence of an IS type thinking bias in the IE discourse and practice has taken a largely traditional and narrow conceptualisation of economic activity as the basis for analysis, such that an uncritical acceptance of *business-as-usual* (BAU) as a starting point has meant that the embedded social discourse that is IE only reflects the concerns, assumptions and ideologies implicit in our current economic system's hegemony according to some authors (Wells and Darby 2006). However, sociologists such as Adam (1995) and some economists (Jackson 2009) and others have begun to challenge this sort of emphasis.

The basic methodology for the IE concept is systems thinking. Its focus so far has mainly been the development of the concept, theory and certain applications connected to energy savings, product design, material cycling and industrial symbiosis within some industrial segments and ecoindustrial parks (Ehrenfeld 2003; Isenmann 2003). However some support the view that the focus of metaphors in this field should be more on material flows and energy, more towards IS: cf. Bey (2001). Others that it should be embracing social processes, business models, and human resource strategies because it is at heart a social and organisational construct more toward the SD end of the spectrum (Cohen-Rosenthal 2000; Harris and Pritchard 2004; Wells and Darby 2006). Other writers also support the softer, wider approach that seeks to bring social complexity into industrial ecology analysis (Korhonen 2005a). Reflexive critique within a developing field such as IE is needed, however as Hermansen (2006) further points out, the current critique of the wider potentially normative aspects of the IE metaphor (and its entailments) may be a hindrance to progress in work on sustainable development.

The question then arises as to what entailments can be identified that may tend to focus IS and IE on different ends of the spectrum. If we utilise an analogy for IS as an *acquisitive approach* and view it as gaining possession over some commodity, an approach that has a clear end point - a static point or outcome in a product, a template, models, materials, construction, accumulation. In this sense we view IS as artefactual, commodity and consumption based in the sense of Adam (1995). In this view IS can be seen as an approach that is well understood by businesses and economists as a normal way to apply BAU and reductionism to familiar problem of seeking efficiencies (which businesses seek at all times) without addressing root causes of our wider systemic sustainability issues.

Using the same logic, then IE could be viewed as a more *participative approach*, one that relates to action, doing, situatedness, contextuality, embeddedness, discourse, communication, interest in participation in activities rather than a focus on specific production outcomes, of being part of a process of development of wider systemic solutions. In this sense IE's entailments give identity defined by function or membership of a whole, taking part, by contributing to the existence and functioning of a community of practitioners or wider system. In a sense IE's potentially wider systems view offers an alternative to BAU thinking which views only the smaller sub-systems as acquisitive and competitive metabolisms. IE therefore questions norms associated with IS (i.e. BAU) and this discourse is currently part of explicit reflection in IE and sustainable development field. The IE discourse replaced talk of closed smaller symbiotic systems with the operations of participative, shared activities and services of mutual benefit on a wider canvas.

In this sense the IS focus is intensely on products and production processes whereas IE has more interest in wider systems. The IS approach is used as a bridge[74] to a wider IE, and IE in turn as a bridge to addressing sustainable development issues. However, the normative implications of IS hegemony are that focus at lower levels in production systems to seek IS gains tends to draw wider (perhaps potentially more sustainable) arrangements apart.

The symmetrical merits of both IS and IE metaphors are that IS is a device for modelling and treating small parts of complex systems in a deterministic manner that makes sense to the micro level of the economic/industrial system on a short temporal basis, but also an approach that opens up ideas about wider IE systems operating across broader networks and over longer timescales. Essentially, the IE metaphor appears to be an older idea grounded in the earlier self-sufficiency of more horticultural type practices whereas IS can be seen as a later one grounded in the use of surpluses obtained from more productive agricultural and industrial practices and the forms of trade that grew out of these surpluses. This is an example of how the agricultural background to our language and industry is easy to forget once metaphors no longer act as metaphors. The approach adopted by IS can be seen as a product of linear framing, inward looking, appealing to the symbiotic economy of a relationship with little view of wider outside environment, a small-scale and utilitarian approach. On the other hand, IE has always been practiced in a tacit way, in horticultural organic cycles for example and it is only recently less important due to relative energy cheapness and the difficulty of creating cyclical systems within the inorganic technosphere.

The step <u>back</u> across to a broader more holistic IE idea is a political step, one that asks the question of how *ought* we to live. This is now highlighted by the political nature of some agendas in the ecological economics discourse that question the BAU approach to industrial production by questioning economic growth assumptions and so the normative dimensions of such questions are also now being addressed; cf. Allenby (2006), Ayres (2008), Berg and Hukkinen (2011), Cohen (1997), Daly (1996),

[74] *Bridge* - a strong engineering metaphor…perhaps a richer word such as *discourse* could also be used?

Ehrenfeld (2008), Hukkinen (2001), Isenmann (2003), Jackson (2009), Korhonen (2008), Kronenberg (2006), Wells (2006) and Wells and Darby (2006).

Mixed metaphors - Focus on IS or IE?

To deliberately introduce the notion of the *mixed metaphor* in a discussion on metaphor here needs some explanation; it is simply a way of exploring the idea of their use as interchangeable terms in some quarters when in reality they are likely incommensurable[75].

That a broad metaphor provides an inspirational framework but only at a lower level does analogy provides a precise metric for measurement, is pointed out by Ehrenfeld (2003). For example, the details of a production process (materials, energy, wastes etc.) can be analysed by the engineer and a way to utilise natural analogues as models for industrial production can be sought (i.e. What can be done?) but this approach does not look at the fundamental issue of whether the product or process being analysed is desirable in the first place (i.e. What ought to be done?), for example an LCA conducted on an ethically or morally questionable product. So where to focus, on IS or IE? Does the transfer of IS ideas into IE and vice versa occur easily? Do those with a focus on IS 'talk past' those with a focus on IE because they address different questions (and vice versa)? For example, IE has to address the *how* on a practical level at some point and so moves towards IS type questions and solutions, conversely IS must look to the *why* from time to time and move towards IE and consideration of paradigmatic issues.

IS and IE seem mutually exclusive in their reluctance to look to detail in the case of IE and the bigger picture in the case of IS; so how do these metaphors crossbreed at all? Is the difference between IS and IE practitioners simply not a matter of differing opinions but rather of participating in different, mutually complementing discourses? The issue of metaphorical entailments to do with norms and values, and the difficulty of utilising metaphors that appear to have entailments opposite to a particular paradigmatic view is described as optional by some (Sfard 1997), only coming to the fore if we choose to endorse them.

The intense debate over the use and application of such metaphors can be transcended to a certain degree by using these devices as metaphors or allegories[76] and not as a strict analogy for how industrial systems need to operate. In this respect, leading theorists in the industrial ecology field have noted that metaphors are neither right nor wrong, only helpful or unhelpful in particular circumstances (Ehrenfeld 2003). Other writers have also pointed out the dangers of too great a devotion to one particular metaphor and rejection of all others leading to theoretical distortions and undesirable practical consequences (Sfard 1997).

What is *sustainable production* and is there an IS focus here? What is *sustainable consumption,* is it a more expansive IE type idea linking directly to Sustainable Development and one that is inherently normative? The further questions that arise from this are: What do these metaphors and models mean from the perspective of different

[75] According to Kuhn (1962), the proponents of different scientific paradigms cannot fully appreciate or understand the other's point of view because they are, as a way of speaking, 'living in different worlds'; cf. Polyani (1958), with different ideas about the importance of solving particular problems, they utilise a different conceptual network and see the world in a different way because of their scientific training and prior experience in research. i.e. lacking a common quality on which to make a comparison.

[76] *Allegory* - an extended metaphor.

actors and do we suffer a level of cognitive dissonance[77] if we attempt to embrace both simultaneously? What are the normative implications of paradigmatic changes in our approach to industrial production and are these implicit in the metaphorical basis of the suggested approaches? What are the implications for the adoption of these ideas in terms of outcomes for our economic approach as well as the environmental outcomes in terms of sustainability?

In terms of systems analysis, things like parameters, buffers, stocks and flows, delays and feedback loops are all lower on any intervention hierarchy than broader paradigmatic aspects relating to system goals, rules and operational paradigms (Meadows 2008). In other words IE type aspects address higher intervention levels. Eco-efficiency, clean production are all low in the systems leverage hierarchy (especially in view of rebound), IS equates to better efficiency, so only equals doing 'less bad' (or BAU). An engineering approach operates at the bottom of the hierarchy and our economic system's goals dictate what is possible from the top of the hierarchy. Only paradigm change trumps the system goals of an incumbent paradigm (Meadows 2008). In this sense each metaphor accuses the other of an approach that relies on too narrow linear deterministic/positivistic engineering models of stocks and flows in the case of IS, or on too broad an holistic, political economy, normative or ideological approach in the case of IE. Is the approach of IS, in particular, focussed too low down on the hierarchy of intervention? Does seeking solutions to the sustainable development challenge need to be focussed at higher intervention levels?

A focus on the impacts instead of causes of impacts has been a prevailing tendency of sustainability science where it has attempted to look at complex systems in a fragmentary manner enabling a reductionist linear approach to simplify analysis (Korhonen 2006). However, some recent issues have asked that we abandon the need to know everything about complex systems before being able to take action at a high enough system leverage point (Meadows 2008) (i.e. looking at affecting causes and not just effects). The use of science to define limits or constraints (something that can be done) is being seen as key in this approach (Jackson 2009; Korhonen 2006).

Industrial, economic determinism also needs to be addressed, do technologies determine behaviour? Once we can design an IE it will all fit together? Does IS risk being viewed as the linear small scale central dogma of the IS/IE engineering community of practice? Does this then allow BAU? We cannot extrapolate simple linear IS systems and ideas to broader larger IE concepts since the systems are too complex and any attempt would be an epistemological error of first order; cf. Bateson (1991). In other words we cannot simply design an IS or a wider IE and it will all fit together, such systems are created as an evolution out of a *community of practice*. There is therefore simply no template to copy; a common context, rules and boundaries would be needed to replicate the same system (Wenger 1998). In this sense it is argued that IS does not take into account temporal aspects related to industrial, political and social institutional change and their linkage to industrial organisation, production, consumption and the economy, and without considering diversity it is a static concept that describes a system being constructed into a steady state (Wells and Darby 2006).

Kalundborg - Designing industrial ecology and industrial symbiosis?

The often quoted symbiosis example at Kalundborg, Denmark (Ehrenfeld and Gertler 1997; Frosch and Gallopoulos 1989), is a joint enterprise with tacit rules, conduct and

[77] *Cognitive dissonance* - discomfort that results from holding two conflicting beliefs - when there is a discrepancy between beliefs and behaviours, something must change in order to eliminate or reduce dissonance.

knowledge and represents interconnected communities of practice within one entity via formal and informal networks benefiting from co-location (Chertow 2005). Such a loosely bound learning organisation or network is one that learns as a social phenomenon through support and strengthening its communities of practice and through social interactions the partner organisations transform tacit knowledge into explicit knowledge (Polanyi 1967). It is for this reason that many studies researching the difficulty in replicating the Kalundborg industrial ecosystem elsewhere have illustrated the issue of contextual differences in implementation (Ehrenfeld and Chertow 2002; Salmi 2008) as well as its unique characteristics (Brings Jacobsen 2006).

There is therefore a gulf between ability to know/have technology that could work symbiotically and working out how this might happen – a mismatch between causal chains of industrial/economic determinism and non-linear social network of reality. The wider social context to IE is largely inaccessible to engineers and social scientists are outside of core engineering. In this sense are practitioners from different ends of the spectrum metaphorically talking past one another? Many contemporary philosophers such as Thomas Kuhn (Kuhn 1962) would respond that the metaphors are *incommensurable* rather than incompatible and because incommensurability entails irreducibility (of vocabularies) but not incompatibility (Rorty 1979), this means there is the possibility of their peaceful coexistence. Do IS and IE make different and conflicting ontological claims about the *wha*t of human industry, about our economy and environmental aspects in terms of sustainability? Can IS be described is BAU but *do less harm*? Can IE be described as seeking a paradigm change and as asking the question 'What ought we to do?'

The risk is that in seeking a local efficiency through IS the approach may be at odds with seeking wider systemic optimal performance of systems. If efficiency maximisation is the goal of IS, this may be in conflict with the goal of optimisation of a wider IE, which in turn may be at odds with a broader systemic goal of sustainable development (or global optimum). In this respect (Hukkinen 2003) further points out that the overall efficiency of larger systems with complex interlinked production webs might require 'inefficiencies' at the lower individual production unit level. Residue generation for subsequent utilisation is a prime hypothetical example here, for instance how can policy makers convince an individual firm that it should adopt <u>increasing</u> its residue generation as the main goal of its EMS, for example in the case where a firm is part of a wider network that demanded it on overall efficiency grounds? cf. Korhonen (2008).

5 Conclusions

This dissertation has described some specific material efficiency possibilities that exist within the forest products and ferrous metals sectors, the associated opportunities for, and institutional barriers to, solid residue utilisation within the Bothnian Arc Region in Northern Finland. The way in which industrial symbiosis and industrial ecology approaches can be applied to the cooperation of multiple, separate industrial sectors was investigated, including the inter-industry utilisation of production residues for the manufacture of novel residue-based symbiosis products. Material efficiency (MEf) and life-cycle thinking are all essential elements of any such approach. The application of sustainable development as a guiding principle in EU public and private sector decision-making and activities however, means that significant institutional change is needed in order to achieve this.

As this thesis has shown, there needs to be an appropriate balance struck between ensuring that real environmental protection needs are always addressed but that this is not to the detriment of developing the more sustainable consumption, re-use and recycling patterns demanded by broad policy. This thesis has argued that the challenge of integrating the paths of environmental sustainability and economic activity, and the role that sustainable development plays as a fundamental political objective, requires that MEf and life-cycle thinking should be given a higher priority as an early part of these new strategies. The potential inter-industry cooperation to achieve improved eco-efficiency to support sustainable development, the residues involved, their characteristics, current and potential utilisations, novel inter-industry symbiosis product ideas and their superior environmental performance were reported.

The important issue of how symbiosis products can be encouraged through addressing institutional aspects for residue handling and the changes that would support increased opportunities for efficiencies were explored and timely practical recommendations made to support this. Here, industrial waste management requires new approaches based on the waste hierarchy and life-cycle thinking, as well as further clarification of the implications of EoW legislation and criteria for product systems with multiple residue streams. Other issues encompass, for instance, the application of best available techniques to material efficiency and waste recovery, and utilisation procedures in process industry environmental regulation, as well as addressing implications of the chemical safety of residue streams and residue-based products. EU instruments claiming to encourage a comprehensive approach to sustainability, including consistency between various instruments, also need to be bolstered by integrated industry related instruments and soft law type approaches acting as guidance at appropriate levels. The responsibilities and duties of producers are also a significant issue here and so placing more emphasis on the development of sustainability management as an integral part of corporate responsibility in these sectors was also investigated and found to be wanting.

An integrating theoretical effort in this dissertation asked whether efficiency seeking is capable of delivering sustainable systems under the dominant paradigm of ecological modernisation if the absolute decoupling of industrial production from environmental impacts depends on wider systemic aspects. The incommensurability of the paradigmatic basis of industrial symbiosis with that of a wider, more sustainable form of industrial ecology was therefore explored and a case made for the value of continued application of both approaches through support for pluralism in our ecological metaphors.

5.1 Barriers and drivers

The objective of the policy and legal review and analysis was to detect current issues with, and outline new ways to, extend policy instruments and regulate and control the use of industrial by-products and residues so as to further higher level sustainability goals. The use of a more integrated approach should have a special emphasis on symbiosis type products (product systems with multiple residue-based raw material streams) as examples of how to effectively and practically implement the waste hierarchy to achieve progress towards sustainability. The technological aspects to residue characterisation, product performance and the implications for recycling are easier to address provided that political will and appropriate resources exist to address these issues.

Waste and product law

This work and its findings support those presented by Allen (2002) and Salmi et al. (2011) on complex sets of waste management rules and definitions being one of the main barriers to material re-use and resource recovery.

The achievement of the sustainability objectives of the WFD necessitates that the status of symbiosis products based on multiple inter-industry residue flows should be addressed covering the identification and determination of workable solutions to potential institutional and practical barriers to efficient recycling of inter-industry residues.

The symbiosis product concepts and case study outlined need to be further clarified in relation to the WFD EoW criteria. If there are end-users and markets for potential symbiosis products, it makes sense to examine the EoW aspects in this particular case. This process should also involve broad-based assessment of the potential adverse impacts and development of appropriate quality standards for both activities and materials. The approach adopted in the UK's WRAP approach is of particular interest in this respect.

Although the use of IS type approaches can help improve the sustainability and environmental performance of modern manufacturing through industrial residue utilisation, the development of residue quality standards that work with EoW criteria are required at national levels to address the status of symbiosis products. Such national standards would aid in the identification and determination of workable solutions to overcome barriers to recycling. The findings suggest that the use of a market focus (the UK's WRAP approach for example) is a key attribute in that it brings the interested actors together to create a focal point for determination of material quality issues related to intended uses. This shared or facilitated approach makes the promulgation of technical standards for utilisation and a market justification easier to accomplish since the players are the experts in their particular residues' characteristics or raw material requirements and the facilitator (e.g. WRAP) and final arbiter (the environmental regulator) are not burdened with developing and maintaining technical expertise in multiple fields outside their areas of core competence.

The implications of the WFD for the manufacturing of such symbiosis products are not entirely clear here, so new thinking is needed from both regulatory authorities and industry covering further development of EoW legislation and criteria with special emphasis on more product-based and innovative approaches for the practical implementation of the waste hierarchy.

In this respect the development of symbiosis products requires further analysis of the WFD prerequisite of residues' potential for losing waste status in law and subsequently also of the effects of the application of product based legislation to potential symbiosis products (i.e. in the form of REACH). Thus a further finding is that manufacturers considering the development of such products need information on the implications of REACH for product systems with multiple residue streams covering: the EoW status aspects, possible broad exemptions for low hazard mineral type substances and articles and treatment of high volume residue streams for example. Neither is there clear information on the potential status of symbiosis products (based on multiple residue streams) as safe fertiliser products (good quality and suitable for plant production) under current Finnish legislation since only generic fertiliser types are specified which do not include symbiosis product-type mixtures.

For the specific case of our symbiosis product concepts based on multiple residue streams, there is a need to establish a clear institutional status for them.

Additionally, local IS potential and its implications for environmental permitting (process industry ecoindustrial park type arrangements as industrial ecosystems for example) could also receive more attention, in particular the issue of system boundaries within which materials could be exchanged and utilised without the issue of waste labelling and justified on an overall MEf basis. Further research here could also focus on the energy efficiency aspects of various recycling and waste management options in addition to MEf (i.e. broader resource efficiency). The issue of industrial system boundaries and the possibilities for symbiotic utilisation of residues within a broader material efficiency context, that also includes a role for process industry regulation, is identified as an additional area that could benefit from more attention. However in this regard the linkages between the objective of sustainable use of natural resources, waste legislation, the environmental permitting of industrial production and use of BAT, would still need to be made more explicit.

The role that environmental permits could play (e.g. concerning recycling of industrial waste flows in the process industries) could be significant in Finland due to the relative size of its process industries in relation the country's economy.

Institutional role

In this dissertation the question of how operational forms of ecosystem ideas can be achieved in practice and what the steps involved in introducing such ideas would be, including motivations for co-operative participation, have all been shown to hinge on institutional aspects that can translate technical potential into beneficial outcomes for the environment and industry. Here, new political will and legal thinking are needed to create a wider enabling environment for industrial symbiosis and the utilisation of industrial residues. Overcoming institutional barriers requires such new thinking from both regulatory authorities and process industry itself encompassing, for instance, stronger focus on new paths towards a more holistic system to encourage IE and IS type activity. The sort of cooperation that is needed between producers in different process industries for more effective use of residual material is however a new proposition in industrial activity. However, intervention through the setting up of institutions to support continued research and cooperation in this area would help create the right climate for seeking further benefits.

Further development of EC waste legislation and the EoW criteria in particular is needed to encourage the development of residue-based products. If markets can be developed for residue-based symbiosis product ideas through effective institutional support, suitable standards developed and their beneficial environmental performance demonstrated, symbiosis products composed of residue raw materials could likely achieve a status comparable to the EoW status and be considered as actual products subject to REACH. This would support sustainable industrial development, but is all dependent on future regulatory development in this area at both EU and domestic levels and the associated compliance costs.

The integrated approach to sustainable industrial development covers many key topics such as resource and material efficiency, life-cycle thinking, low carbon solutions and sustainable use and management of natural resources. The integration of sustainability into management approaches is therefore important. The findings indicate that sustainability and life-cycle management are not receiving enough management focus at the moment and that the forest products industry in particular is not receiving enough guidance at either the EU level or via national steering and regulatory frameworks. Here, findings indicate that IS and related efficient recycling and increased waste recovery and utilisation activities deserve more focus as a part of overall sustainability management.

5.2 Environmental aspects

The recycling of industrial residues offers a viable option to reduce the amount of waste needing final disposal through efficient recycling provided that there are no negative impacts such as risk to human health and the environment. Utilisation of waste flows as valuable secondary raw materials clearly contributes to the long-term goal of progress towards sustainability of industrial operations through advances in material efficiency. New symbiosis products would also create benefits here in terms of economic and social sustainability particularly at the local level.

Environmental impact

This thesis has argued that a more holistic approach to thinking concerning the utilisation of process industry residues is required, where beneficial utilisation of industrial residues is viewed as a logical step towards the goal of sustainability through sustainable development. The concept of industrial symbiosis offers opportunities to attempt to seek and achieve reductions in environmental impacts, including CO_2 emissions through supporting the utilisation of residues with smaller emission footprints in place of virgin materials.

The recycling of industrial residues into secondary raw materials for use in new symbiosis products can in particular reduce the environmental impacts associated with the manufacturing of equivalent products that use virgin primary raw materials and the associated landfill construction and landfilling operations to deal with their associated production wastes.

Life cycle thinking and IS/IE ideas offer opportunities for strategic thinking on local and regional scales concerning inter-process industry residue management and symbiosis product development. Product life cycles and particularly the environmental performance of products during their whole life cycles are among the new priority focus areas. In this respect this research on residue-based product concepts has shown that there are potential environmental benefits associated with the utilisation of multi-stream industrial residues as raw materials for potential symbiosis products in terms of relatively low GWP figures and high level of exergy efficiency provided that the associated manufacturing processes would be not energy-intensive and very limited or no primary raw materials would be used. The examples of GWP figures associated with products based on primary raw materials and of relatively energy intensive waste treatment processes indicate at the general level that the environmental burden increases significantly the more energy (non-renewable in particular) and virgin raw material are used. It was assumed in this study that the multi-stream residues would be burden-free secondary raw materials and it also needs to be highlighted that the actual applications of such potential secondary products would involve additional extensive environmental and human health and safety assessments.

From a life cycle perspective the utilisation of industrial residues improves the material efficiency of industrial processes. Symbiosis products offer an excellent opportunity for companies operating in the same region to improve their environmental performance (product carbon footprints in particular), here process industries can improve their environmental performance (substitution of products based on virgin raw materials and avoided waste disposal to landfill) through full utilisation of the local potential for industrial symbiosis with special emphasis on material efficiency and more efficient recycling of residue materials.

New drivers for increased focus on resource efficiency and symbiosis products in general will continue to come from the need to address environmental impacts, for example the discussion of climate change and targets to reduce the CO_2 emissions at national and EU-level could be the next step for increasing the use of residue-based products. However, first there is much work ahead in this research field, where smaller carbon footprints for additional residue-based product concepts must be proven by further research results.

Environmental suitability

The main findings from the specific symbiosis product concept aimed at soil amelioration were that the industrial residue-based soil amendment formulation made from steel industry desulphurisation slag and fibre industry fly ash, paper mill sludge and lime waste shows promise.

Only Ba and V, [which are not included in either the revised eco-ecological criteria and the related assessment and verification requirements for the award of the Community eco-label to soil improvers (EC 2006b) or the Finnish legislation of fertiliser products (Ministry of Agriculture and Forestry Finland 2011)], indicated potential availability under natural conditions. The results demonstrated that the proposed soil amendment concept would probably fulfil some of the essential elements for qualification in terms of lawful use therefore. Thus, in addition to Ba, possible V availability to plants requires further research on potential plant utilisation.

Issues with concentration limits that are set by regulatory authorities for utilisation of residues was also highlighted by the results from this more sophisticated BCR type approach - where the use of total concentrations in limit values describing potential environmental impacts was shown to be insufficient in describing the real mobilisation capacities and behaviours of the target species under extreme pseudo-environmental conditions. These results will help inform future regulatory decision making concerning likely environmental availability of trace elements

5.3 Sustainable development and ecological thinking

Although this dissertation has included some technological aspects of industrial production relating to material characteristics and environmental performance, it has also attempted to address some of the difficult challenges that arise in bridging the gap between technical potential and implementation arising out of institutional contexts.

The reduction and optimisation of energy consumption and the closure of material cycles is a reasonable objective when striving for the conservation of non-renewable resources. With the participation of industry sectors and through active residue management efforts, real accomplishments might be attainable. The steel, pulp and paper inter-industry environment offers opportunities to strive for symbiotic solutions capable of relieving the pressure for the utilisation of industrial residues and moving towards the goal of improved sustainability. Here, the consideration of wider more holistic networks of material utilisation may offer new ways to overcome barriers to inter-industry utilisation.

A more sustainable industrial development trajectory will require more holistic and innovative approaches to be adopted in future encompassing the utilisation of wastes as a valuable resource to be recycled for further use and the application of systems and life cycle thinking for both improvement of environmental performance and minimisation of environmental impacts. Improving industrial sustainability at smaller scales of lower complexity with tighter system boundaries is an area in which IS could be an acceptable approach because it contributes to the less unsustainable use of resources and to increased material and energy efficiency. The IS approach therefore lends itself more easily to consideration as a normal engineering problem, allowing a reductionist approach in the complicated yet linear system segments to achieve optimisation, but always having an eye to the bigger picture by way of its linkage to broader more complex IE concepts.

A real move towards true sustainable development (SD) requires a paradigm shift that implies a change in the way we understand the global environment-economy system. Essentially, it has been shown how IE type ideas equate with a firm move towards SD thinking; whereas IS type ideas equate more with a business-as-usual (BAU) approach, with short term efficiency seeking, however IS also acts as a useful bridge to broader IE thinking and ultimately towards SD.

It can be seen that most studies relating to materials characterisation, in terms of the potential of residues to be manipulated to potentially increase materials efficiency, are essentially convergent problems that lend themselves to relatively straightforward analysis. However it is at the top of the pyramid, where we are seeking broader systemic responses in society, that we face the divergent problems relating to how to approach the multiple avenues that need to be addressed effectively and simultaneously.

These policy and legal analysis, material management and characterisation studies, signal the possibilities that multidisciplinary work can open up for making progress towards SD in terms of: IS in the short term; legal and policy changes in the medium term; and in the use of more SD orientated metaphors for the organisation and operation of industrial systems in the longer term. In order to achieve this, a form of metaphorical pluralism seems to offer a way forward, an approach that understands the contradictions that we live within our everyday lives. Such pluralism would operate in terms of accepting short term BAU and seeking efficiencies from IS type ideas that can lead to wider sustainability thinking, and seeking out broader IE type ideas in the medium term.

The continued use of these metaphors as a bridge to, or discourse on, SD by business and society can assist in addressing the changes we need to make in our overall narrative concerning the effective sustainable operation of our environment-economy system.

Capturing the difference in emphasis between IS and IE or where the transition from one approach to the other occurs can be simplified by two questions. If we ask ‘What is possible?’ this is a question engineers understand as a need to seek solutions to a problems in our human economy and one we are good at addressing using reductive science. However, the infinitely more complex and normative idea that IE suggests seems to ask is ‘What ought we to do?’ and it this question that highlights our current predicament, inviting new broader responses and ideas that could help address the problem of achieving sustainable systems.

The conflicting narratives we have concerning the real meaning of sustainable development, on the one hand, and the way we understand and also currently expect our economy to operate, on the other, both act as high level system rules that society has available to apply. The dominant rule presently operates so as to default to a BAU outcome for the economy acting as a subcomponent of a continually degraded environment system. The BAU approach does seek efficiencies that have some environmental merit however, but these efficiencies are overwhelmed by our economic system's rebound effect, caused simply by the growth imperative. The current situation is therefore still very much one of BAU and not SD.

This work argues for the use of both IS and IE in a continued metaphorical pluralism, looking to both approaches and where they can augment each other in order to move towards the sort of transitions that must be made in our thinking on sustainable systems.

5.4 Practical implications

This research has considered the opportunities that an industrial symbiosis approach offers in steel, pulp and paper mill waste, by-product and residue utilisation by the enhancement and development of larger and more diverse inter-industry industrial symbioses where residue-based novel product concepts show some promise such as residue-based liming and fertiliser products as well as other the use of residue combinations in cementitious product applications.

In achieving a recycling society there is the need to continuously improve regulatory procedures so that they do not act as impediments to successful and environmentally acceptable residue utilisation. The utilisation of materials or substances defined as 'waste' (in symbiosis products and consideration of the application of product-based legislation and associated standards to these products) will require further legislative development. The new waste regime allows recycling and reuse of residual materials, but involved operators will most likely need more information on the potential EoW status of both combined residues and any resulting symbiosis products. On a practical level this means that more attention should be paid to product-based legislation, standards and innovation to prevent waste generation and to encourage recycling and waste recovery where this is unavoidable. In Finland, the key issues to be addressed encompass the need for a comprehensive approach to recycling covering, for instance, new quality and environmental compliance criteria for certain recycled materials to achieve EoW status (e.g. similar to the UK's EoW *waste protocols* approach) and an innovative approach to environmental permitting (e.g. guidance on MEf BAT) .

This work identifies the potential for new institutions to be set up to encourage and facilitate industrial symbiosis activities through which companies should be encouraged to cooperate as a dynamic network of different industrial sectors in order to bridge the gap of lacking knowledge. In this way the different drivers in supply chains, the pressure and new practices for more effective material use might come from within these networks itself. Such collaboration between actors will also help support derivation of soft law type guidance such as EoW quality protocols to open up further possibilities for new ways to formulate, describe, quality assure, and justify the utilisation of process residues instead of disposal to landfill. In addition, specific arrangements to promote symbiotic networks and advice, such as an institutional focus for such activity, is a linkage that is specifically absent in Finland formally and often only occurs via academic intermediaries as highlighted by our Finnish case study. A good example highlighted in this work that could be used as a template is the UK's National Industrial Symbiosis Programme (NISP).

As an illustration of the complexities and the lack of holism and contextual sensitivity of current institutional frameworks, the issue of how one might justify making <u>more</u> of a particular residue (e.g. that forms part of a wider symbiosis system boundary that results in a gain in overall system eco-efficiency) and arguing for its EoW status, plus addressing subsequent product based legislation such as REACH, may easily bring the problems associated with the interplay of many of the discussed issues into a clearer focus. In other words how to develop guidance and agree upon it where it is not a waste minimisation issue but rather a wider eco-efficiency approach if a proven secondary commercial application is possible. Increased residue utilisation therefore requires more attention from all actors with respect to practical, local and product-orientated perspectives. Developments in Finnish domestic legislation are clearly needed to enable the recovery of valuable material and energy losses by reutilising residues with characteristic technological and environmental suitability. Where existing restrictions on the utilisation of residues means that environmental permits are required for their use, this is often related to the specification of the nature of the originating processes' not being defined in law rather than on the environmental suitability of the material in question. An increased emphasis on the use of the actual properties of residues in determining their utilisation options rather than focussing simply on their origin is therefore an area that would benefit from more attention and one that is assisted by residue characterisation and utilisation research such as this.

5.4.1 Soft law

It has been shown that it is clear that the EU encourages Member States to increase the use of a combination of regulatory and economic instruments. In addition to this there is the so called *soft law* approach which unlike norms and rules, is not part of legislation but can give direction however. Overcoming institutional barriers through traditional environmental steering instruments would require strong focus on the creation of an enabling environment through appropriate incentives, policies, regulations and taxes as well as soft law guidance jointly with consistent technical guidance on material efficiency, but also producer responsibility and an innovative approach to environmental permitting.

For example, the creation of enabling conditions for systems to encourage industrial symbiosis activities allied to the operation of the WFD should encompass clear definition of when certain waste ceases to be waste (via EoW criteria and specifications). Similarly, soft guidance on how large footprint process industries such as steel, pulp and paper should address the issue of MEf (perhaps under the auspices of environmental permits), as well as guidance for small to medium sized manufacturers, could also benefit production efficiencies and reduce environmental impacts. Here, the results of the analysis suggest that an innovative approach to environmental permitting and a comprehensive approach to recycling, encompassing new quality and environmental compliance criteria for certain recycled materials as soft law type approaches, should receive more focus in future decision-making. The specific example of WRAP (and how it plays a strong role in upstream activities related to process industry wastes and residues regulated by the environmental permitting authorities and the idea that markets are the key to resource recovery) is central to the overall approach that could be adopted. Here the development of residue quality protocols will aid in maximising benefit from unavoidable wastes.

The role of EU level guidance (in the form of horizontal BAT guidance on MEf under permitting regimes for integrated pollution prevention and control of large process industries) could have a role in future however and would augment the efforts of initiatives similar to WRAP and MOTIVA type approaches but would also act as a driver for large process industries such as the energy, steel and pulp and paper sectors.

5.4.2 Potential of symbiosis products

The experimental manufacture and environmental performance residue-based products via recycling of materials from integrated pulp and paper mills, carbon steel plants and mining operations into secondary raw materials for use in potentially novel symbiosis products (e.g. soil amelioration pellets, low competence concrete and mine filler product concepts) has shown that this kind of waste utilisation could be an acceptable and more sustainable option for industrial processes.

This study demonstrates the proposed soil amendment would probably fulfil some of the essential elements highlighted in the EoW criteria of the WFD regarding the circumstances under which losing waste status may be at issue. Enabling such residue utilisation would, from a life-cycle perspective, improve the material efficiency of industrial processes and clearly contribute to the sustainable use of natural resources. Reusing and recycling industrial residues decreases the utilisation of virgin raw materials and most likely the amount of generated waste in need of final disposal thus also supporting the implementation of the general priority order of waste management set in the waste hierarchy.

This research has shown that further research into that manufacturing of symbiosis products instead of landfilling has the potential to improve the environmental performance of local industrial systems. In addition, these potential symbiosis products have local industrial applications and the soil amelioration pellet and low competence concrete have also wider market potential. The manufacturing of potential secondary products causes lower environmental burdens where the residues are classified as burden-free. Environmental benefits are realised through, in particular, the substitution of symbiosis products for products based on virgin primary raw materials as well as through avoided environmental burdens associated with landfilling and related construction activities for waste management of residues. In general, process industry should be encouraged to identify and assess the local potential for industrial symbiosis covering more efficient recycling of materials and energy. However, the successful development and manufacturing of such symbiosis products and their integration into normal production systems requires information on the application of EoW legislation and criteria on product systems with multiple residue streams.

EU waste policy strongly supports recycling and reuse but residue-based products still face challenge under the waste-based regulatory regime. New thinking is therefore needed from both industry and regulatory authorities encompassing, for instance, stronger focus on local aspects in this respect.

The implications of the WFD EoW approach for the development of symbiosis products consisting of several residues together is however unclear and this implies that the current regulatory framework faces some challenges in meeting the demands of a recycling society and increased material efficiency. A major question is whether the REACH Regulation would apply to residue-based symbiosis products if their creation makes them no longer legally classified as waste. Since symbiosis products are by their nature likely to be reliant on the specific local nature of residue streams and made in relatively small quantities, this issue is likely to be almost always case-specific. Since REACH costs act as a barrier, the size of a residue-based product's market might mean that the residue raw material waste status and subsequent treatment via an environmental permit path could still be the preferred approach. Thus, potential manufacturers of such symbiosis products need information on the implications of REACH for product systems with multiple residue streams covering the EoW status aspects, broad exemptions for low hazard mineral type substances and articles, and treatment of high volume residue streams for example.

The EU's waste policy is built on the waste hierarchy which strongly supports recycling and re-use of waste materials, however, innovative material and product solutions may continue to face a challenge under the waste-stream based regulatory regime. Enabling such residue utilisation would, from a life-cycle perspective, improve the material efficiency of industrial processes and contribute to the sustainable use of natural resources.

5.5 Theoretical implications

The findings support ideas presented within the industrial ecology (IE) discourse such as those concerning the value of more closed material cycles and use of residues from one industry process as valuable raw materials for another. It similarly supports approaches aimed at reducing environmental impacts, in line with industrial symbiosis (IS) thinking (Allenby, 1999; Allenby and Cooper 1994; Ayres and Ayres 1996) and the benefits of local industrial ecosystems (Heino 2006), and that a more sustainable world will require increased focus on integrated industry-society-environment interactions to ensure responsible approaches to industrial activities (Graedel and Allenby 2010). The results also support the ideas presented in literature concerning sustainability, industrial ecology and recycling such as those of Daly (1996), Daly and Farley (2004), Jackson (2009), Graedel and Allenby (2010) and Reuter et al. (2005), concerning the need for significantly more focus on efficient resource use, the fixing of limits to resource availability and consumption and the use of more integrated approaches. Additionally, the findings support the results of previous studies and ideas presented by many authors in the field concerning the need for interaction among actors, such as Ashton (2009), Chertow (2000; 2007), Ristola and Mirata (2007) and the key role of flexible legal tools and normative institutions (Graedel and Allenby 2010). Support is also given to the notion of Baumgartner (2011) regarding the need to recognise both normative and practical aspects of sustainable development and the need for both strategic thinking and action.

Other previous studies have noted the benefits of industrial symbiosis including Heino (2006), Heino et al. (2008), Sokka et al. (2011a; 2011b), and the importance of integrated approaches to decision-making in accordance with life cycle thinking (Finnveden et al. 2009). This work supports these and points out the added significance of the systemic industrial ecology approach and achieving progress towards sustainability via material efficiency through more closed material cycles, supported by various previous studies such as Allenby and Cooper (1994), Basu and Zyl (2006), Ehrenfeld (2007), Korhonen (2004a) and Nurmesniemi et al. (2007).

In general, the findings support the points made within the sustainability science discourse on the need for more focus on comprehensive and integrative approaches, identification of interconnected elements at all levels, multiple stakeholders and incentives for the implementation of sustainable practices (Kates et al. 2001; Baumgartner 2011).

Ecological metaphor implications

Part of the theoretical effort of this thesis questioned whether efficiency seeking is capable of delivering sustainable systems under the dominant paradigm of ecological modernisation if the absolute decoupling of industrial production from environmental impacts depends on wider systemic aspects. The meaning and role of ecological metaphors was therefore discussed in relation to their use in advancing progress towards sustainable systems.

This dissertation has shown how IE and IS approaches can contribute significantly to the advancement of a more sustainable society and economy across wide system boundaries where process industry is linked to society through a broad network of institutions covering various socio-economic and normative elements. The results suggest that a more comprehensive approach is needed and this should involve the application of life cycle and systems thinking, and innovative approaches to residue utilisation and environmental control for the minimisation of overall environmental burdens and impacts over defined system boundaries. The need for a more holistic approach is needed to promote increased utilisation of residues in beneficial interactions.

The theoretical discussion of the application of IS and IE metaphors addressed the question of the use of linear approaches versus wider metaphors and their respective roles in addressing the issue of sustainability. The approach of IS with its more objective, a more linear subset approach to the existing human economy that can be studied without ideological baggage, is one of *industrialising nature's models*, one that asks what can be achieved and how can we proceed, was described as one where a narrow even deterministic focus is possible. On the other hand the IE metaphor, a normative and ideological approach of *naturalising industry and the economy*, was described as one with a philosophical discourse on paradigms, that asks how ought we to proceed, one that is wider in scope, subjective and questions political economy, an approach that invites a paradigm change in terms of the view of society's relationship with nature.

Pluralism in metaphors

Why more than one metaphor? As pointed out by Sfard (1997), tension between seemingly conflicting metaphors offers protection against theoretical excesses, against theory translated into an general prescription, where exclusivity becomes the worst enemy of success i.e. exclusivity is often equated with certainty whereas multiple metaphors encourage the questioning of generally accepted classification out of which critical theory is more likely to arise.

Some metaphors may be more attractive than others because of their accessibility, flexibility, imaginativeness or aesthetic value. But the choice is up to the researcher, what do they want to achieve? If looking at construction of a local industrial sub system and reduction of environmental impacts then the IS metaphor seems best since it brings forward issues of representation, construction of tangible systems, things being designed in detail and built within a controlled defined space such as simple residue utilisation arrangements. But if on the other hand a researcher is concerned with wider issues such as sustainability, then the wider IE metaphor approach may be more helpful as one that brings social factors to the fore and thus deals with an incomparably wider range of complex aspects that would defy a detailed analysis in all areas. Here, Wells (2006) points out that the current focus of both approaches is in any case more towards defining the elements of the system, of data acquisition and quantification and methodologies for modelling, with the general approach being dominated by the modernist culture of mechanistic positivism. However IS has engineering practicality as a firm driving force but opens one's eyes to wider IE ideas as a bridge to thinking more realistically about truly sustainable systems. In this sense Wells (2006) also calls for an *integrated epistemology* able to integrate rational scientific knowledge with a more personally implicated level of engagement. Metaphors are important in challenging world views, acting as prisms through which we begin to understand the world around us in different ways. Challenging dominant paradigmatic thinking is therefore a key role of metaphors; cf. Ehrenfeld (2003), Korhonen (2005b) and Wells (2006). This is an important role of ecological metaphor that this thesis has attempted to elucidate and help progress.

We also seem to have a cultural disposition to more readily emphasise competitive and predatory relationships over mutualistic and symbiotic ones. Promoting a more participative approach over that of the acquisitive will involve a change in the general perception of the effectiveness of these approaches in moving towards more sustainable systems in the face of practical necessity.

On accepting the reality of the sustainability challenges that face us we should utilise all the metaphors available in attempting to move from a position of short-sighted disregard for our predicament (though an appeal to seeking efficiencies at the IS end of the spectrum only), to a more creative adaptation (through contemplation of more paradigmatic changes concerning society's model of production and consumption as envisaged in broad IE), and ultimately closer to a firmer idea of what development towards truly sustainable human systems might be and what they might look like. Adopting a form of *pluralism of metaphors* in the interim offers a way forward. Through the application of IS on the linear small-scale, by buying time and making local improvements through ecological efficiencies, IE and ecological economics can also be used for seeking solutions to wider systemic issues where scale and complexity invites the need for a new narrative to support it as a bridge to sustainable development.

As pointed out by Sfard (1997), revolutionaries tend to believe there is a mutual exclusiveness to new ideas and a need for zealous declaration of devotion to new approaches in order to bring to critical scrutiny existing ones. However such single-mindedness runs the risk of polarising the debate. Transformation however, retains the social institutions needed to guide us through the narrow window of opportunity to a new system that establishes limits and reorientates the economic approach. In this respect, much recent writing on the general theme of environmental sustainability runs the risk of being charged with adopting approaches that might be seen as 'rants against modernity' or 'laments at the human condition'; cf. Jackson (2009). However, a more fundamental view of our industrial systems' input assumptions in terms of energy and material costs and quantities, challenges the idea of modernity, in that the environmental limits now require more sustainable systems be developed through more participative approaches. Taking a systems view of our environment is therefore key for the future. Looking to nature as a mentor, wherever possible, and not just a source of raw materials, looking to learn from it rather than dominate it, and not treating other parts of the ecosystem as a commodity or a *standing stock,* but as described by Ehrenfeld (2008) rather 'a context to our existence', offers a way forward.

This work has described some of the material possibilities that are modulated by institutional actors within a small part of the current system of industrial production. It describes why the current system delivers small efficiencies over local, short temporal basis but why absolute decoupling of growth from environmental impact depends on wider systemic narrative change. The incompatibility of the paradigmatic basis for IS with that of wider IE and SD ideas was explored. Short term solutions to improve efficiencies by addressing materials symbiosis opportunities and changes to institutional arrangements were described that also intimate the challenge to efficiency seeking under the dominant paradigm in terms of achieving sustainable systems. The continued utilisation of efficiency related metaphors as a bridge to more systemic and perhaps ultimately more effective and realistic metaphors that proceed on the basis of achieving true sustainability in our systems is suggested.

5.6 Significance of this work

A more sustainable industrial development trajectory will require more holistic and innovative approaches be adopted in future and this dissertation attempted to take a similarly multi-faceted approach to the research thesis from its broad policy perspectives to the specific focus of attention on certain individual case studies.

This work has attempted to put multidisciplinary research and thinking into practice and necessitated the author address and include elements of other research fields outside core engineering areas, including the interdisciplinary field of industrial ecology, and benefitted from a research methodology and ideas from the social sciences.

Concrete proposals for addressing institutional aspects were given that are novel, timely and derived from an integrated analysis of multiple frameworks. The use of concept symbiosis product formulations and both their environmental and feasibility assessment as a device for assessment of opportunities and barriers to residue utilisation is a novel approach.

The presented work also described some of the issues concerning the epistemological facets of multidisciplinary research and the emerging interdisciplinary field of industrial ecology which also have resonance with how we approach problems and predicaments in our normal everyday lives outside of the technology/science paradigm. The adoption of this approach has resulted in the identification of many fruitful areas for further research.

5.7 Recommendations for further research

As costs pressures increase, due to improved technical and operating standards for waste management, the introduction of various EU Member States' fiscal measures in the form of taxes to divert waste away from final disposal options, and the increased pressure on new disposal site development, mean that interest will continue to grow in the possibilities for reprocessing a wider and wider range of materials and substances previously mainly consigned to final disposal as wastes. Whilst current waste legislation and policy do promote the reuse of waste materials and recycling targets in general, meeting the demands of more sustainable industry and a recycling society will require further development of both more effective waste and product-related legislation and standards.

Increasing the sustainability and environmental performance of modern process industry has the potential to be advanced through inter-industry residue utilisation and development of novel symbiosis products however. More research focus is therefore needed on the assessment of other realistic possibilities for residue utilisation and on the specific case of secondary raw material products generation from multiple source residue streams in particular. Life cycle assessment (LCA) provides a useful tool here in the comparison of adjacent product types and/or processes and should continue to be undertaken in the assessment of any promising residue-based symbiosis products in order to analyse the potential benefits regarding relative environmental impacts, material efficiency, energy consumption and waste generation. More detailed and focussed LCA and sustainability assessment studies on specific IS products, covering other impacts categories in addition to GWP, are therefore needed.

The difference in the scale of residue production between the chosen process industries used in this study means that research into the type of symbiosis products presented in this work can only act as a partial solution to (in particular) the steel industry's needs. However, the approach outlined could be useful in making a contribution towards the reduction of environmental burdens in local industrial networks. Marketing research into the realistic scale of production and utilisation of these residue-based product concepts would therefore be a further useful step in this area of research.

In order to improve institutional arrangements in Finland for addressing sustainability through material efficiency, waste and product law, and the promotion of symbiosis activities, further research into the potential role for a nationally coordinated forum involving industry, academia and environmental regulators should also be undertaken. Creating a focus for activities in this area would encourage further work on symbiosis opportunities.

For the specific case of the soil amelioration pellet concept, guidelines for high quality, safe and most appropriate fertilisers are needed. Establishment of standards and focus on chemical properties and related impacts are also among the main issues in this context. In general, fertiliser products should be accompanied by extensive safety and quality information covering all raw materials. The legal status of symbiosis products (based on multiple residue streams) as safe fertiliser products, could be specifically assessed in future research. Here the issue of specific toxicity studies relating to intended target applications as well as the solubility of trace elements in natural environmental conditions are areas where further research is also needed.

Future research could also focus on ways to address barriers related to other practical examples of residue recycling into symbiosis product concepts and the steps that need to be taken in order to develop clear guidance on the institutional status of such approaches and resulting residue-based products. There are many other areas where the development of such symbiosis products may be possible. Here, additional case study work may be useful in looking at process industry residue possibilities in symbiosis with the metal working, brick, tile, cement, road building and building/construction products industries for example.

Further, other interesting avenues for research attention include the possibilities to adjust process industry operations to improve the recycling and utilisation potential of residues flows and by-products in a way that does not harm the production of primary products, such as the attempted in-process management of residue qualities in the same fashion as for primary product streams. Residue quality fluctuations within installations and across different installations and opportunities for active management of residue characteristics in residue generating processes require more research.

Afterword

There's a well-known *bon mot* concerning a tourist lost in the deepest countryside who asks a local farmer for directions back to the Capital city. To which the farmer replies: 'Well Sir, if I were you, I wouldn't start from here!' Having some country blood in my family, I can relate that with impunity and make the observation that there is also some wisdom in the farmer's cryptic response. After all, if you want to get somewhere, then is it not better to start from a point from where you have a better chance of reaching your goal? How does this relate to my subject matter? Well if your goal is a new way of approaching and responding to the predicament of industrial sustainability, then might the response of attempting a reform of business-as-usual be seen as simply tinkering with a broken model, when what might be required is a radical rethink and transformation in our approach, a change to the very the axioms that underpin our current systems? However, to be so bold as to paraphrase the eighteenth-century philosopher, historian and economist David Hume (1711-1776); it is not obvious how we move from the descriptive to the prescriptive (Hume 2000). This work has tried to address a very small part of the question of where we *can* start from with the tools at hand, but the bigger and altogether more important question still remains, and that asks in which direction *ought* we to proceed...

'Education cannot help us as long as it accords no place to metaphysics. Whether the subjects taught are subjects of science or of the humanities, if the teaching does not lead to a clarification of metaphysics, that is to say, of our fundamental convictions, it cannot educate a man and, consequently, cannot be of real value to society.'

Ernst Friedrich Schumacher 1973

'It is not knowledge, but the act of learning, not possession but the act of getting there, which grants the greatest enjoyment.'

Johann Carl Friedrich Gauss 1808

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Annexes

Annex 1 ProDOE research activities (ProDOE 2010)

Pro-environmental Product Planning in a Dynamic Operational Environment Now and in the Future - Methods and Tools (ProDOE)

D.Sc. Kari Heiskanen, D.Sc. Olli Dahl, Lic.tech. Carl-Johan Fogelholm, D.Sc. Olli Salmi, Lic.Tech. Helena Mälkki, Lic. Tech. Sanni Eloneva, M.Sc. Maaria Wierink, M.Sc. Nani Pajunen, M.Sc. Gary Watkins, M.Sc. Mikko Mäkelä and M.Sc. Laura Kainiemi
Aalto University School of Science and Technology
PhD Janne Hukkinen, LL.D Ari Ekroos, M.Sc. Jarkko Levänen, LL.M, Eeva-Maija Pusa and LL.M Inga-Liisa Paavola - **University of Helsinki**
D.Sc. Timo Fabritius and PhD Jyrki Heino - **Oulu University**

BACKGROUND AND RESEARCH HYPOTHESIS

The research is an ambitious effort to combine an interdisciplinary approach within a systemic framework in order to research the economic, legal and/or administrative ways of steering development towards closing or optimising resource cycles. Closure (optimisation) of resource (material) cycles in industry are only possible if all chemical, physical, technical, economic, legal, administrative, environmental, and social issues are considered together in a systemic way. Research in ProDOE has been divided into a 4 Team Matrix to address each of these important fields as follows:

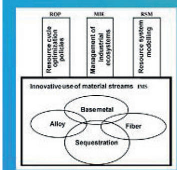

Figure 1. 4 Team Matrix

1. **ROP** Resource Cycle Optimisation - law and policy, waste, incentives, role of BAT, product policies and standards, new ways to regulate
2. **MIE** Management of Industrial Ecosystems - industrial ecology and ecological efficiency indicator modification, product life cycles and sustainability
3. **IMS** Innovative use of Material Streams - the "inter-engineering platform", technical boundary conditions, utilisation feasibility, metal slags, fibre cycle residues and Co2 sequestration, stream impurities, compositional changes and combination of streams, connecting systems
4. **RSM** Resource System Modelling - model for product designers, scenario development for MIE and ROP

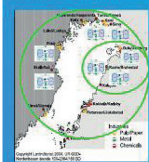

Figure 2. Bothnian Arc

BOTHNIAN ARC AS A REAL RESEARCH CASE

The Bay of Bothnia, located between Sweden and Finland, is the northernmost basin of the Baltic Sea. The locations of industrial plants (chemicals, metals and pulp and paper) around the Bothnian Arc next to this sensitive bay have faced and solved many environmental challenges and problems offering huge possibilities in future to both the EU and globally. The Bothnian Arc therefore offers an ideal research platform for multidisciplinary ProDOE research.

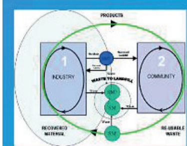

Figure 3. Material flows in a society

SYMBIOSIS VS ECOLOGY?

1 - IS Installation
2 - IS Local
3 - IS/IE Sub Regional
4 - IE Regional
5 - IE Transnational?

OTHER ACTIVITIES IN THE PRODOE PROJECT

- 21 scientific papers and 18 scientific conference papers have been published before August 2010
- An International Symposium (4S) with 47 doctoral students and 10 professors was arranged (see: http://4s.mekpros.fi/)
- 2 ProDoe seminars with Finnish Industry.
- 2 Nordic Recycling days both with Luleå University of Technology and Swedish and Finnish industry
- 4 doctoral theses have been produced (3 of these doctors now serve in industry and the public sector.)

MAIN OUTPUTS

ROP: The regulatory basis is contradictory, as the financial steering seems according to proposals to support reducing waste but the legislative control prevents this from being effective. The new EU and national waste legislation cannot solve all the questions. What is required, are new types of regulating tools that are globally efficient or at least cover the EU level regulation, which could promote material and energy efficient material flow. This could mean that the whole concepts of waste and products must be re-thought.

MIE: A management model of the Bothnian arc industrial ecosystem was developed on the basis of common pool resource principles. A life-cycle inventory model on the steel and zinc production system around the Bothnian arc was used to illustrate the effects of increased waste recovery on greenhouse gas emissions. A diagnostic was provided of the key socio-cognitive challenges in the governance of the industrial ecosystem.

IMS: Many candidate residues and streams for intensified utilisation, intra- and inter-process industry applications have been found. New products from metal, slag and other residues have been developed (leading to reduction of CO2) and areas for further studies on quality modifications and symbiotic novel products have been identified. This has involved both intra and inter-company development in the metallurgical, chemical, pulp and paper industries and there are also possibilities to improve regional and societal material and energy efficiency with flexible co-operation between industry and localities.

RSM: LCA models of Bothnian arc zinc and iron cycles have been developed and the effect of use of recycled raw material for total CO2 balance have been modelled. The main drivers which have an effect on industrial waste management have been identified and the drivers that determine waste management solutions in an industrial setting in Finland have also been identified.

Annex 2 Other relevant publications

In addition to the seven publications forming this compilation thesis, the author was also involved in the production of the following articles which, although referenced extensively and having been instrumental in the development of some of the ideas and directions that this work took, do not form a direct part of this compilation dissertation:

i) Dahl, O., Hynninen, P., **Watkins, G**., & Martikka, M. (2008). *Environmental Management and Control, Volume 19 Paper Making Science and Technology* (2 ed., Vol. 19). (O. Dahl, Ed.) Helsinki: Finnish Paper Engineers' Association/Paperi ja Puu Oy.

ii) Salomaa, E., & **Watkins, G**. (2009) Environmental Performance and the Cost of Water Pollution Control Compliance in Industry. *Sustainable Development, **11**(19(5)), 325-336.*

iii) Dahl, O., Nurmesniemi, H., Pöykiö, R., **Watkins, G**. (2009) Comparison of the characteristics of bottom ash and fly ash from a medium-size (32 MW) municipal district heating plant incinerating forest residues and peat in a fluidized-bed boiler. *Fuel Processing Technology **90***, 871-878.

iv) **Watkins, G**., Pöykiö, R., Nurmesniemi, H., Dahl, O. (2010) Earth Construction and Landfill Disposal Options for Slaker Grits. *Journal of Applied Sciences, Engineering and Technology **2**(8),* 757-764.

v) Nurmesniemi, H., Dahl, O., **Watkins, G**., Pöykiö, R. (2010), Slaker grits from the causticising process of a pulp mill – a potential fertilizer and liming agent material in agriculture and forestry. *International Journal of Materials Engineering Innovation **1**(3/4),* 312-324.

vi) Dahl, O., Nurmesniemi, H., Pöykiö, R., **Watkins, G.** (2010) Heavy metal concentrations in bottom ash and fly ash fractions from a large-size (246 MW) fluidized bed boiler with respect to their Finnish forest fertilizer limit values. *Fuel Processing Technology **9** (11)*, 1634-1639.

vii) Mäkelä, M., **Watkins, G**., Dahl, O., Nurmesniemi, H., Pöykiö, R. (2010) Integration of solid residues from the steel and pulp and paper industries in forest soil amendment products. *Journal of Residuals Science and Technology 7/4*, 191-198.

viii) Nurmesniemi, H., Pöykiö, R., **Watkins, G**., Dahl, O. (2010) Total and extractable heavy metal, phosphorous and sulfur concentrations in slaker grits from a causticizing process at a pulp mill used as soil amendment. *Chemical Speciation and Bioavailability **22**/2*, 87-97.

ix) **Watkins, G**., Pöykiö, R., Nurmesniemi, H., Dahl, O., Mäkelä, M. (2011) Total and extractable element concentrations in bed sand material from a medium-sized (32 MW) municipal district heating plant incinerating peat, stumps, sawdust and recycled wood. *Fuel Processing Technology **92(6)**,* 1195-1202.

x) Puheloinen, E.-M., Ekroos, A., Warsta, M., **Watkins, G**., Harju-Oksanen, M., & Dahl, O. (2011). Industrial Emissions Directive (IED) enforcement and other environmental protection law development ideas (Teollisuuden päästödirektiivin (IED) voimaansaattaminen ja muita ympärisympäristönsuojelulain kehittämisajatuksia), (in Finnish). Ympäristöministeriön **6**/2011. Helsinki: Ympäristöministeriön.

xi) Mäkelä, M., Nurmesniemi, H., **Watkins, G**., Pöykiö, R., Dahl, O. (2012) Secondary steel mill slags with pulp and paper mill solid residues for soil amendment: mineralogy, relevant physicochemical properties and trace element availability. *International Journal of Materials Engineering Innovation **3/1***, 1-16.

xii) Husgafvel, R., Nordlund, H., Heino, J., Mäkelä, M., **Watkins, G**. and Dahl, O. (2012) New recycled cross/inter-industrial residue flows (Uudet poikkiteolliset kierrätysmateriaalivirrat), (in Finnish). Suomen ympäristö **10**/2012, Ympäristönsuojelu, 90 s. Suomen ympäristökeskus (SYKE), 73-77.

xiii) Mäkelä, M., **Watkins, G**., Pöykiö, R., Nurmesniemi, H., and Dahl, O. (2012) Utilization of Steel, Pulp and Paper Industry Solid Residues in Forest Soil Amendment: Relevant Physicochemical Properties and Heavy Metal Availability. *Journal of Hazardous Materials **207-208**,* 21-27.

xiv) Lilja, R., Saloranta, M., **Watkins, G.** (2012) Promoting Material Efficiency in Environmental Permits – Present State and New Opportunities (Teollisuuden Materiaalitehokkuuden lupaohjaus – nykytila ja uudet mahdollisuudet), (in Finnish). Ympäristöjuridiikka **4**/2012, 45-76.

xv) **Watkins, G.**, Husgafvel, R., Paavola, I. (2013) Editorial - The renewal of Waste Framework Directive: Industrial residues - Is recycling now more straightforward? *Waste Management **33**,* 1-3.

xvi) Husgafvel, R., Pöykiö, R., Nurmesniemi, H., Dahl, O., **Watkins, G**., Mäkelä, M. and Tikka, J. (2013) Forest fertilizer properties of ash fractions from a 32 MW municipal district heating plant incinerating peat and solid wood-based fuels. ISWA BEACON 2nd International Conference on Final Sinks, 16-18 May 2013. 55-60.

xvii) Pöykiö, R., Nurmesniemi, H., Dahl, O., **Watkins, G.** (2014) A three-step fractionation scheme for non-process elements in green liquor dregs from a kraft pulp mill. *Journal of International Environmental Application & Science* **9**(1): 48.58 (2014).

Errata and corrigenda

Errata[78]

Any post-publication errata will be as shown on an insert at this page location.

Corrigenda[79]

Paper II: In the first sentence in Section 5, the term ‘side-product’ is used instead of the correct term ‘by-product’.

Paper IV: In Figure 3, the term ‘side-product’ is used in addition to the correct term ‘by-product’.

[78] Errata are production errors (i.e. errors introduced during the publishing process).

[79] Corrigenda are author's errors.

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This doctoral dissertation describes novel material efficiency possibilities that exist within selected process industries, the associated opportunities for, and barriers to, residue utilisation through industrial symbiosis within the Bothnian Arc Region in Western Finland. It describes the inter-industry cooperation and materials involved, novel product ideas, their environmental performance, as well as how such symbioses can be encouraged through addressing institutional aspects for residue handling and the changes that would support increased opportunities for such symbiotic efficiencies. It further explores whether efficiency seeking is capable of delivering sustainable systems under the dominant paradigm of ecological modernisation. The incommensurability of the paradigmatic basis of industrial symbiosis with that of a wider, more sustainable form of industrial ecology is also explored and a case made for the continued application of both through support for pluralism in our ecological metaphors.

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